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Title: **Immersive Three-Dimensional Virtual Reality Modeling for Case-Specific Presurgical Discussions in Cerebrovascular Neurosurgery**

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Abstract

Background: Adequate surgical planning includes a precise understanding of patient-specific anatomy and is a necessity for neurosurgeons. Although the use of virtual reality (VR) technology is emerging in surgical planning and education, few studies have examined the effectiveness of immersive VR during surgical planning using a modern head-mounted display.

Objective: To investigate if and how immersive VR aids presurgical discussions of cerebrovascular surgery.

Methods: A multiuser immersive VR system, BananaVision^{TM}, was developed and used during presurgical discussions in a prospective patient cohort undergoing cerebrovascular surgery. A questionnaire/interview was administered to multiple surgeons after the surgeries to evaluate the effectiveness of the VR system compared to conventional imaging modalities. An objective assessment of the surgeon's knowledge of patient-specific anatomy was also conducted by rating surgeons' hand-drawn presurgical illustrations.

Results: The VR session effectively enhanced surgeons' understanding of patient-specific anatomy in the majority of cases (83.3%). An objective assessment of surgeons' presurgical illustrations was consistent with this result. The VR session also effectively improved the decision making process regarding minor surgical techniques in 61.1% of cases and even aided surgeons in making critical surgical decisions about cases involving complex and challenging anatomy. The utility of the VR system was rated significantly higher by trainees than by experts.

Conclusion: Although rated as more useful by trainees than by experts, immersive 3D VR modeling increased surgeons' understanding of patient-specific anatomy and improved surgical strategy in certain cases involving challenging anatomy.

Running Title: Immersive VR for Cerebrovascular Surgery

Keywords: presurgical planning, simulation, rehearsal, VR, microsurgery, aneurysm, arteriovenous malformation

Introduction

A precise understanding of microsurgical anatomy is essential for neurosurgeons. Surgical trainees spend years learning intricate neuroanatomy through case observations and conventional two-dimensional (2D) representations such as textbook illustrations.[1, 2] Moreover, since neurovascular anatomy varies significantly from patient to patient, a precise understanding of patient-specific anatomy is required for cerebrovascular surgery.

To date, patient-specific three-dimensional (3D)-printed physical models and virtual reality (VR) models have been utilized to enhance surgical planning and education as they convey comprehensive 3D anatomical information to surgeons.[2-4] Advanced simulation models have also been combined with mixed reality technology.[5] VR models require no extra cost to render models and allow the user to repeat sessions. Recent study confirmed that VR models have advantages over 3D-printed models including the ability to zoom, greater image resolution, and greater model durability.[3] Although 3D-printed models allow the use of depth perception and are easier to manipulate,[3] "immersive" VR environments with modern head-mounted displays (HMDs) provide more convincing stereopsis than stereoscopic viewing of 2D images, allowing the user to perceive depth in a similar way to 3D-printed models.[6-9] Gerig et al. have demonstrated that HMDs are superior to 2D screens in terms of depth perception, regardless of additional artificially recreated depth cues.[6]

Although studies examining the utility of VR systems have shown promising results, there have been few prospective studies utilizing "immersive" VR technology including HMDs. Additionally, VR systems have not yet been widely integrated into clinical practice, possibly due to concerns about cost and model construction times.[7-10] Therefore, in this study, we introduce the newly developed VR modeling program, BananaVision^{TM} (Colorado State University), which has the features of fast processing time, multiuser functionality, and high usability. We evaluated this system during the presurgical planning of cerebrovascular surgeries.

Materials and methods

VR software (Video 1)

The VR modeling program BananaVision^{TM} was developed at the Department of Biomedical Sciences, Colorado State University to improve anatomical learning through digitization. This platform rapidly (<1–2 minutes) generates 3D models using patient's medical images such as computed tomography (CT) and magnetic resonance imaging (MRI) scans in VR space. The image processing procedure is provided in **Supplementary Data 1**.

Wearing typical HMDs, the users can maneuver and observe these 3D models in VR space. Using handheld controllers, the user can easily adjust the images to visualize the skull, brain parenchyma, and vasculature. The user can change the size of objects, mobilize objects in any direction, and slice objects on any plane. An "eraser" function enables the user to simulate craniotomies. Because two surgeons wearing HMDs could simultaneously access the same VR space, surgical teams could share patient-specific anatomy and surgical views while discussing a surgical plan or teaching trainees (**Figure 1A**).

Facility and surgeons

The VR system utility for neurosurgery was independently assessed in Hokkaido University Hospital. Two interconnected personal computers with the BananaVision^{TM} were placed in a conference room beside the neurosurgical ward in the Hokkaido University Hospital. Surgeons could freely use this system at any time.

Fourteen surgeons participated in this study and were sorted into two groups based on their level of neurosurgical experience. The trainee group included 10 neurosurgical residents (postgraduate years 3–6) and one clinical fellow, who had not performed an entire microsurgery independently. The expert group included 3 board-certified neurosurgeons, who had independently performed over 500 cerebrovascular microsurgeries.

Study design

This study was approved by the institutional review board of Hokkaido University Hospital (No. 018-0291). Informed consent was obtained from all participants, including surgeons and patients. The study design is summarized in **Figure 1B**.

All patients with cerebrovascular disease (CVD) scheduled or under consideration for microsurgery between April 2019 and December 2019 were enrolled in this study. Patients with CVD included patients with cerebral aneurysm, arteriovenous malformation (AVM), and occlusive CVD such as moyamoya disease (MMD). After the patients were admitted, staff surgeons and attending residents routinely discussed and created surgical plans using conventional imaging methods, including MRI, CT, CTA, digital subtraction angiography (DSA), and perfusion imaging. The attending residents presented the surgical plans during our weekly case meetings prior to surgery, and the plans were discussed by all neurosurgical staff. Presurgical schematic illustrations were routinely presented for educational purposes. Attending surgeons then freely decided whether or not to use the VR system.

Outcomes were evaluated 3–4 months after surgery. A favorable outcome was defined as a modified Rankin Scale of either 0 or 1 or as neurological improvement after surgery relative to the patient's preoperative state.[11, 12]

Questionnaire/interview survey

When presurgical planning sessions with the VR system were conducted before surgery, a simple questionnaire/interview was administered to both primary and assistant surgeons after surgery to evaluate the effectiveness of the VR sessions. The questionnaire included the following three questions: (**Q1**) Did you think the VR session effectively increased your understanding of patient-specific anatomy? (**Q2**) Did you think the VR session effectively enhanced your decision-making ability regarding a minor surgical technique (e.g., patient's head position, order of the dissection)? (**Q3**) Did you think the VR session effectively enhanced your decision-making process regarding a critical surgical technique (e.g., surgical approach, range of craniotomy)? The surgeons indicated their agreement with each question using a 5-point Likert scale ranging from 1 to 5 (“1: Strongly disagree,” “2: Disagree,” “3: Neutral,” “4: Agree,” and “5: Strongly agree”). The effectiveness of the VR sessions in each case was represented by the primary surgeon’s evaluation.

Objective assessment of surgeons’ anatomical understanding

To objectively evaluate whether the VR session improved surgeons’ understanding of patient-specific anatomy, we evaluated presurgical schematic illustrations drawn by surgeons who had attended presurgical planning sessions. Presurgical illustrations were compared with the actual surgical videos, and the precision of the presurgical illustrations was rated by an independent expert surgeon who did not take part in performing aneurysm surgeries. They were rated from 0 to 10 in terms of six categories: (1) projection of aneurysms (0–2 points), (2) location of parent arteries (0–2 points), (3) location of branch arteries (0–2 points), (4) the surrounding anatomical structure (brain, cranial nerve, or dura matter/tentorium) that was mainly attached to the aneurysm (0–2 points), (5) other anatomical structures that were attached to the aneurysm (0 or 1 point), and (6) other anatomical structures in the surgical view (0 or 1 point). The artistic element was not considered in this rating system. Information about when (pre- or post-VR) and by whom the presurgical illustration was drawn was blinded to the rater for evaluation purposes.

Statistical analyses

Statistical analyses were performed using the SPSS Statistics® (IBM). The unpaired population rates between the two groups were compared using the chi-squared or Fisher’s exact tests as appropriate. The paired ordinal scale data were compared using the Wilcoxon matched-pair signed-rank tests. A p-value <0.05 was considered statistically significant.

Results

Patients' characteristics

During the study period, 38 patients (15 aneurysms, 10 AVMs, and 13 occlusive CVDs) were candidates for cerebrovascular surgery, and surgeons chose to conduct presurgical VR sessions in 20 (52.6%) patients (12 aneurysms, 7 AVMs, and 1 MMD) (**Figure 2**). In the majority of patients with occlusive CVD who underwent extracranial-intracranial (EC-IC) bypass, VR sessions were not conducted because the manner in which EC-IC and indirect bypasses were performed was relatively standardized. VR was used during presurgical planning for only one patient with occlusive CVD (MMD), for whom VR was used to identify and preserve the middle meningeal artery. In contrast, VR was used during presurgical planning for the majority of aneurysm and AVM cases (75% and 70%, respectively).

Of the 20 patients for whom VR was used during presurgical planning, one patient's surgery for cervical arteriovenous fistula was abandoned because of a complication during the preoperative embolization session. Of note, one patient with multiple aneurysms was selected for observation rather than surgery after estimation of their surgical risk during a VR session (**Supplementary Data 2**). Therefore, the remaining 18 patients underwent surgery and were analyzed. Patient information is summarized in **Table 1.** The patients comprised 10 men and 8 women aged 22–76 years.

All surgeries except one (Case 2) went as planned during the presurgical VR sessions. In the exceptional case, surgeons planned to clip the patient's aneurysm; however, they found a perforator strongly attached to the aneurysm intraoperatively and changed the plan to aneurysmal coating. We observed three surgical complications: two cases of perforator injury (ischemic stroke) and one case of wound infection. Seventeen patients (94.4%) eventually experienced favorable outcomes.

Effectiveness of presurgical VR sessions

Thirty-six responses to questionnaires were obtained from both primary and assistant surgeons across 18 surgical cases. The VR sessions were evaluated as "effective" for increasing surgeons' understanding of patient-specific anatomy in 83.3% of cases (**Figure 3A**) and as “effective” at enhancing the decision-making process concerning minor surgical techniques in 61.1% of cases (**Figure 3B**). In some cases (27.8%), VR sessions were also evaluated as “effective” for enhancing the decision-making process regarding critical surgical techniques (**Figure 3C**). Surgeons never answered “Disagree” or “Strongly disagree” in response to any question. However, 3 surgeons (21.4%) experienced mild motion sickness after a VR session.

The trainee group was significantly more likely to answer “Strongly agree” in response to Q1 than the expert group ($p<0.01$) (**Figure 3D**). The trainee group was also more likely to answer “Strongly agree” or “Agree” in response to both Q2 and Q3 than the expert group ($p<0.01$ and $p=0.01$, respectively) (**Figure 3E, F**).

The cases in which the primary and assistant surgeons agreed with all questions (Q1–3) were challenging cases involving complex anatomy such as (1) multiple aneurysms (Case 9), (2) a recurrent basilar artery (BA)-superior cerebellar artery (SCA) aneurysm after coiling (Case 11), (3) a medial temporal AVM fed by the passing anterior choroidal artery (Case 14), and (4) an occipital AVM fed by a passing artery (Case 17).

Objective assessment using presurgical schematic illustrations

After surgery, 24 total illustrations (14 pre-VR and 10 post-VR) drawn by 9 surgeons (1 expert and 8 trainees) for cases of 9 anterior circulation aneurysms (MCA; n=5, internal carotid artery; n=2, anterior communicating artery; n=2) were collected and rated. The score of the illustrations significantly increased after VR sessions relative to before VR sessions ($p<0.05$) (**Figure 4**). Interestingly, although expert surgeon’s scores were higher relative to trainee’s score even before VR sessions, their scores also increased after VR sessions.

Illustrative cases

Case 17

A 26-year-old male with a left occipital AVM elected to undergo surgery (**Figure 5A–C**). Preoperative 3D-DSA revealed three feeders from the posterior cerebral artery to the AVM. Of these, one of the feeders passed through the nidus and supplied blood flow to normal brain parenchyma. Although the spatial association between the feeders, drainer, and other surroundings was complex, the surgeon clearly understood the anatomy after using the surgical view during a VR session (**Figure 5D**). The surgery was performed as planned (**Figure 5E, F**).

Case 11

A 66-year-old male was admitted to the hospital with a rapidly regrowing BA-SCA aneurysm, which had previously ruptured and been coiled (**Figure 6A–C**). After discussing treatment options with the patient, surgeons decided to microsurgically repair the aneurysm. Although the distance between the intra-aneurysmal coils and the origin of posterior cerebral artery was sufficient to insert a clip, the distance between the coils and the origin of the SCA was significantly small to insert a clip without sacrificing the SCA (**Figure 6B**). Therefore, surgeons planned to use clipping in conjunction with a superficial temporal artery (STA)-SCA bypass. Three surgical approach options were initially discussed: (1) a transsylvian approach, (2) a subtemporal approach, and (3) a subtemporal approach with an anterior petrosectomy. A VR session was subsequently conducted involving two experts and the attending residents. In the VR session, the surgeons determined that the retro-carotid space between the internal carotid artery and anterior clinoid was significantly narrow to use as a surgical corridor to the aneurysm in the transsylvian approach (**Figure 6D**). We also simulated a subtemporal approach combined with an anterior petrosectomy (**Figure 6E**); however, we determined that the space created by the anterior petrosectomy would not be beneficial to approach both the aneurysmal neck and the proximal BA. We therefore utilized a standard subtemporal approach and successfully accomplished both an STA-SCA bypass (**Figure 6F**) and clipping (**Figure 6G, H**).

Discussion

We prospectively tested the efficacy of a multiuser VR system during daily presurgical planning sessions for cerebrovascular surgeries. As a result, high utilization rates were observed before aneurysmal and AVM surgeries possibly due to the strengths of this system such as fast processing time and high usability.[7, 8] Although the fundamental information volume was similar as the original CTA data,[13] the surgeons could better understand patient-specific anatomy by observing 3D patient models in immersive VR space.[14] As expected, the educational effect of VR was greater in the trainee group; however, even expert surgeons benefited from VR sessions. The multiuser functionality of the system also enhanced presurgical planning and education because surgeons could discuss and teach surgical strategy while sharing the same surgical view in VR space.[15]

Notably, an objective assessment revealed that VR sessions improved surgeons' anatomical understanding in both expert and trainee surgeons. This new research method allows for an objective assessment of surgeons' performance, which is emphasized in the current competency-based education paradigm.[16, 17]

Virtual models in cerebrovascular surgery

Recent trends toward increased endovascular techniques and work-hour restrictions are decreasing the surgical experience of trainees and increasing the difficulty of surgery.[18, 19] Presurgical simulation of patient-specific anatomy is therefore increasingly required for proper presurgical planning and education without threatening patients' safety. During aneurysm surgery, the most important strategic objective is to secure the proximal parent artery while avoiding the risk of aneurysmal rupture. Therefore, information regarding the projection of the aneurysm and the spatial association between the proximal and distal arteries are vital considerations when planning these surgeries. VR sessions could have aided the decision-making process regarding surgical approaches. Similar benefits were also observed in AVM surgeries, specifically regarding the strategy for securing the main feeding artery while avoiding the occlusion of the passing artery and draining vein before nidus resection.[20]

Limitations

This study has several limitations. First, it included a limited number of cases and could not demonstrate a direct correlation with clinical outcomes such as reduction of operating time or blood loss and neurological improvement. Second, the self-selection of the user to participate in VR session could introduce a bias in the result during subjective assessment since he/she was most likely to rate the session favorably.

The largest shortcoming of the BananaVision^{TM} was likely its inability to fuse multimodal images. Several investigators have successfully built more realistic 3D graphics that include information regarding cranial nerves and the brain surface.[21, 22] Another limitation is the current availability of other VR platforms.[15, 23-25] Integrating VR systems with other devices such as navigation systems[26-28] and augmented reality technologies[29-31] will likely produce the next generation of surgical planning tools. Additional technologies such as procedural simulation with haptic feedback and/or tissue deformation would also be another direction.[23-25, 32] However, since these advanced systems will be expensive and time consuming, only disease- or purpose-specific usage of advanced technologies should be considered in the future.[7, 33]

Conclusion

Although the educational impact of VR sessions was greater in surgical trainees than expert surgeons, 3D modeling of patient-specific imaging effectively increased surgeons' understanding of patient-specific anatomy and helped determine surgical strategy in certain cases involving complex and challenging anatomy.

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Figure Legends

Fig. 1

A: Virtual reality (VR) station with BananaVision^{TM} installed together with hand controller and a head-mounted display. Collaborative case discussions were conducted while sharing the same immersive VR models.

B: Study design.

Fig. 2 Flow chart of study participants during study period.

Abbreviations AN; aneurysm, AVM; arterio-venous malformation, AVF; arteriovenous fistula, CVD; cerebrovascular disease, CTA; computed tomography angiography, MMD; moyamoya disease

Fig. 3

A-C: Bar graphs of primary surgeons' responses to the three questions for each case.

D-F: Bar graphs of the rates at which all surgeons answered "Strongly agree" or "Agree" to the three questions. $^*p<0.05$, $^{**}p<0.01$.

Fig. 4 Presurgical schematic illustrations and scores (Case 5)

A: A conventional three-dimensional (3D) computed tomography angiogram (CTA).

B: A VR session. The users could view 3D models at any angle, simulate craniotomies, and experience surgical approaches in immersive VR space.

C-E: Intraoperative photographs of the secured parent artery (**E**), the exposed aneurysm (**F**), and the surgical site after clipping (**G**).

F, G: An example of presurgical illustrations before and after VR sessions. The scores tended to be higher in experts than in trainees, and all scores increased after VR sessions. $^*p<0.05$

Fig. 5 An arteriovenous malformation (AVM) case (Case 17)

An AVM was located in the left medial occipital lobe (**A**). A conventional digital subtraction angiogram (DSA, **B**) and rotational DSA (**C**) showing three feeders and one drainer (asterisk). One of the feeders (**F-2**) was passing through the nidus and was supplying blood flow to normal brain parenchyma. Through VR models, surgeons could experience an operative 3D view and understand the spatial relationships between the nidus, drainer, and feeders (**D**). Intraoperative photographs showing that the feeders and drainer were precisely identified (**E**), and the nidus was removed as planned without injuring either the passing artery or drainer (**F**).

Fig. 6 A case of a regrowing BA-SCA aneurysm after coiling (Case 11).

A conventional DSA (**A**), rotational DSA (**B**), and 3D-CTA (**C**) showing regrowth of a BA-SCA aneurysm after coiling. The VR simulation of a transsylvian approach (**D**) showed that the postero-inferior space of the internal carotid artery was too narrow to approach the aneurysm (asterisk). The simulation of a subtemporal approach (**E**) combined with an anterior petrosectomy (arrow) showed that the surgical corridor through the anterior petrosectomy was not beneficial for approaching the aneurysm or for securing the proximal basilar artery. Intraoperative photographs (**F-H**) showed that the SCA was anastomosed with the STA. The aneurysm was clipped as planned using the subtemporal approach.

Abbreviations PComA; posterior communicating artery, PCA; posterior cerebral artery, SCA; superior cerebellar artery, ACA; anterior cerebral artery, ICA; internal carotid artery, MCA; middle cerebral artery, CP; clinoid process, BA; basilar artery, STA; superficial temporal artery, CN IV; fourth nerve

Supplemental Digital Content

Supplementary Data 1 BananaVision^{TM} and image processing

Supplementary Data 2 A case of multiple aneurysms who selected for observation

Video Legends

Video 1 Multiuser immersive virtual reality system

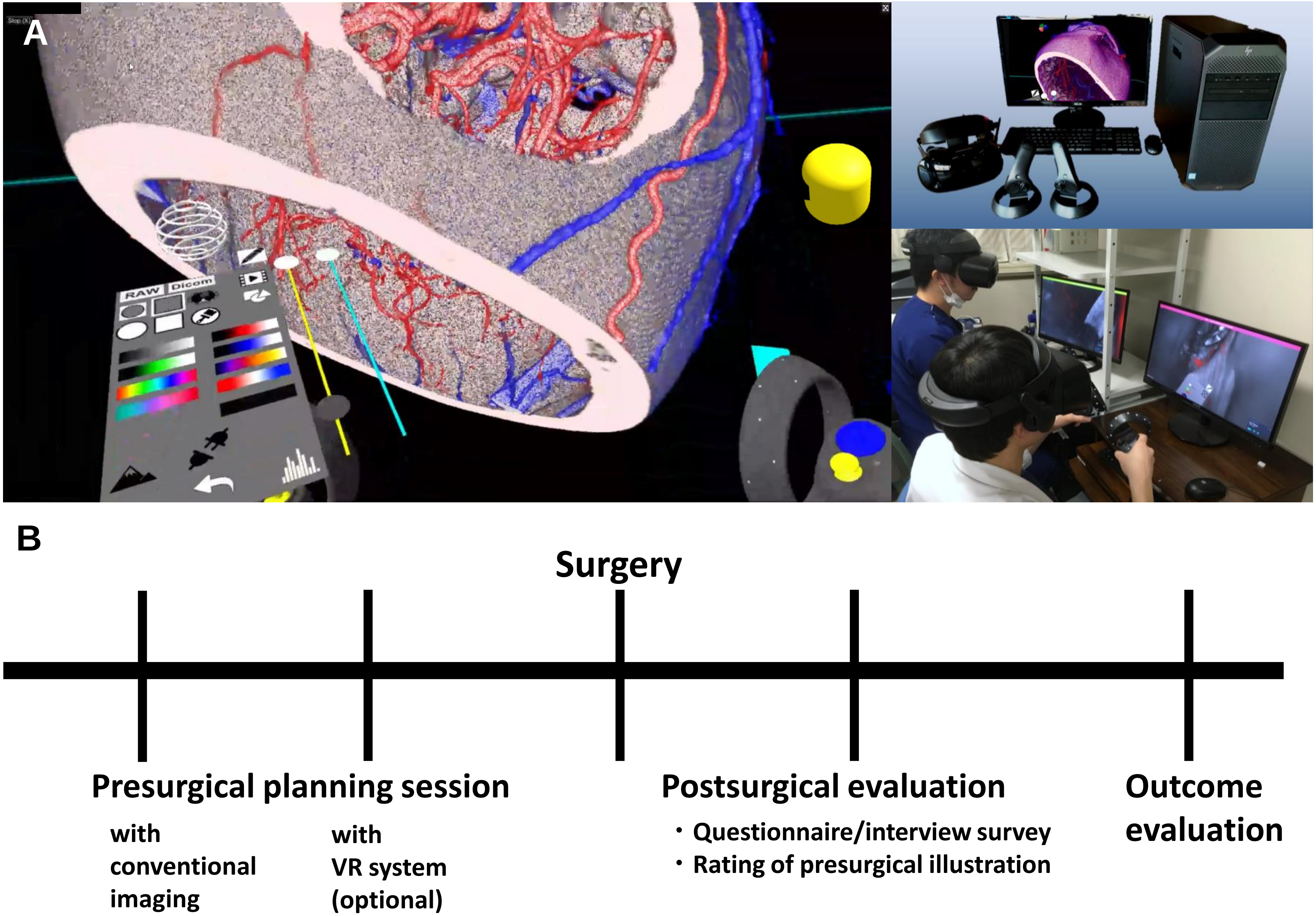
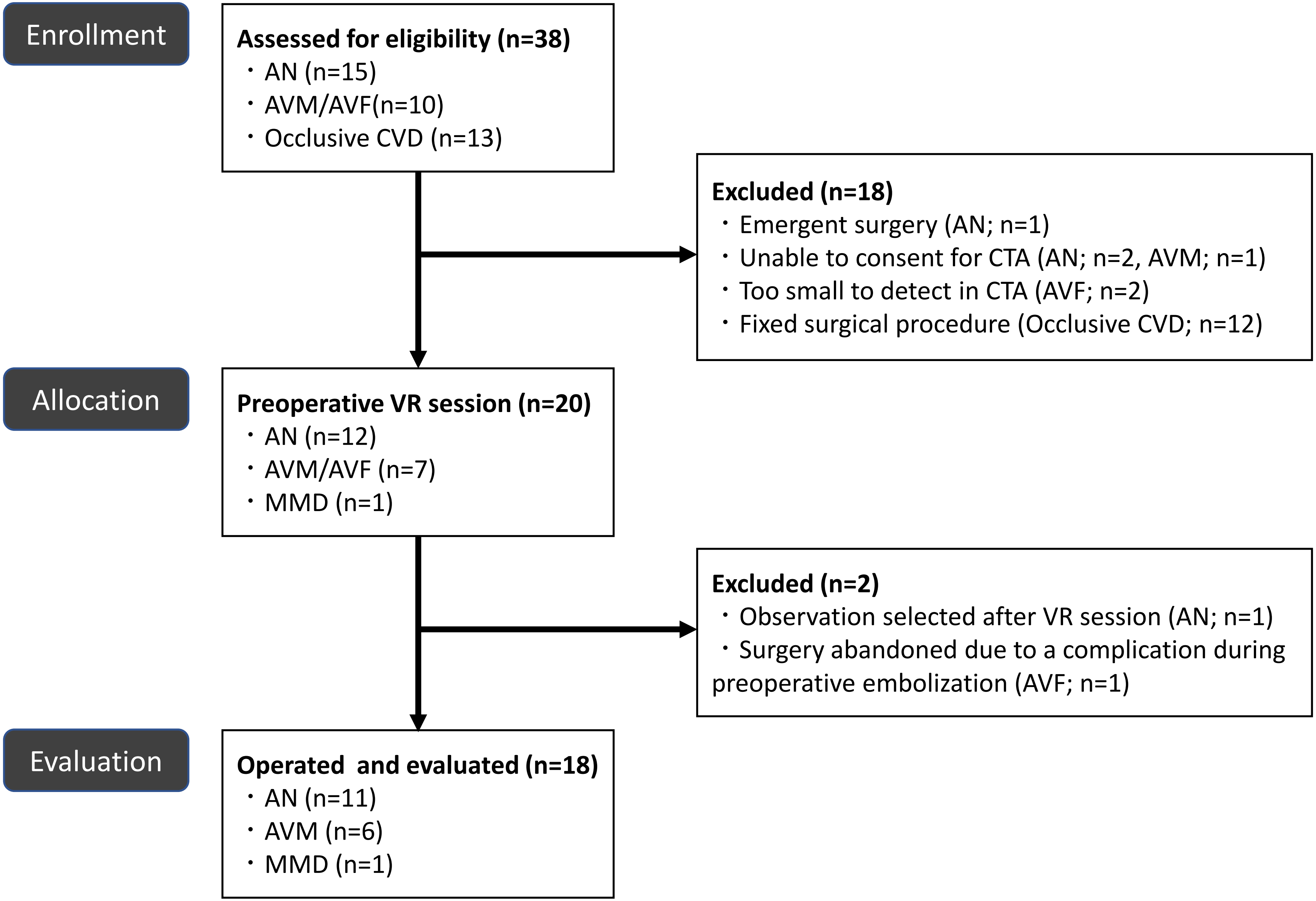

A
Stop (X)
RAW
Dicom
B
Surgery
Presurgical planning session
with conventional imaging
with VR system (optional)
Postsurgical evaluation
・Questionnaire/interview survey
・Rating of presurgical illustration
Outcome evaluation

Fig. 1



Enrollment

Assessed for eligibility (n=38)
・AN (n=15)
・AVM/AVF(n=10)
・Occlusive CVD (n=13)

Excluded (n=18)
・Emergent surgery (AN; n=1)
・Unable to consent for CTA (AN; n=2, AVM; n=1)
・Too small to detect in CTA (AVF; n=2)
・Fixed surgical procedure (Occlusive CVD; n=12)

Allocation

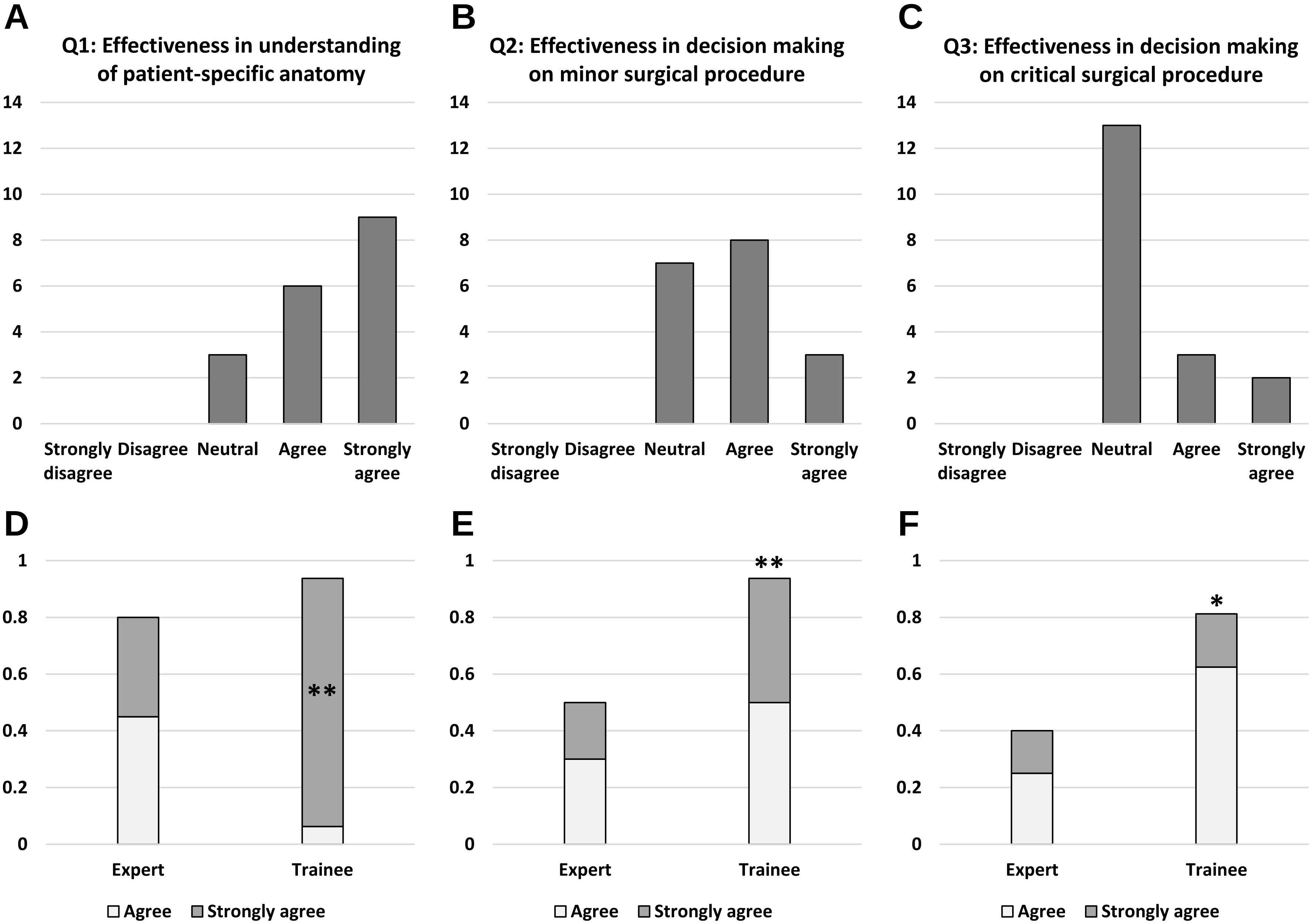
Preoperative VR session (n=20)
・AN (n=12)
・AVM/AVF (n=7)
・MMD (n=1)

Excluded (n=2)
・Observation selected after VR session (AN; n=1)
・Surgery abandoned due to a complication during preoperative embolization (AVF; n=1)

Evaluation

Operated and evaluated (n=18)
・AN (n=11)
・AVM (n=6)
・MMD (n=1)

Fig. 2



Q1: Effectiveness in understanding of patient-specific anatomy

Q2: Effectiveness in decision making on minor surgical procedure

Q3: Effectiveness in decision making on critical surgical procedure

Fig. 3

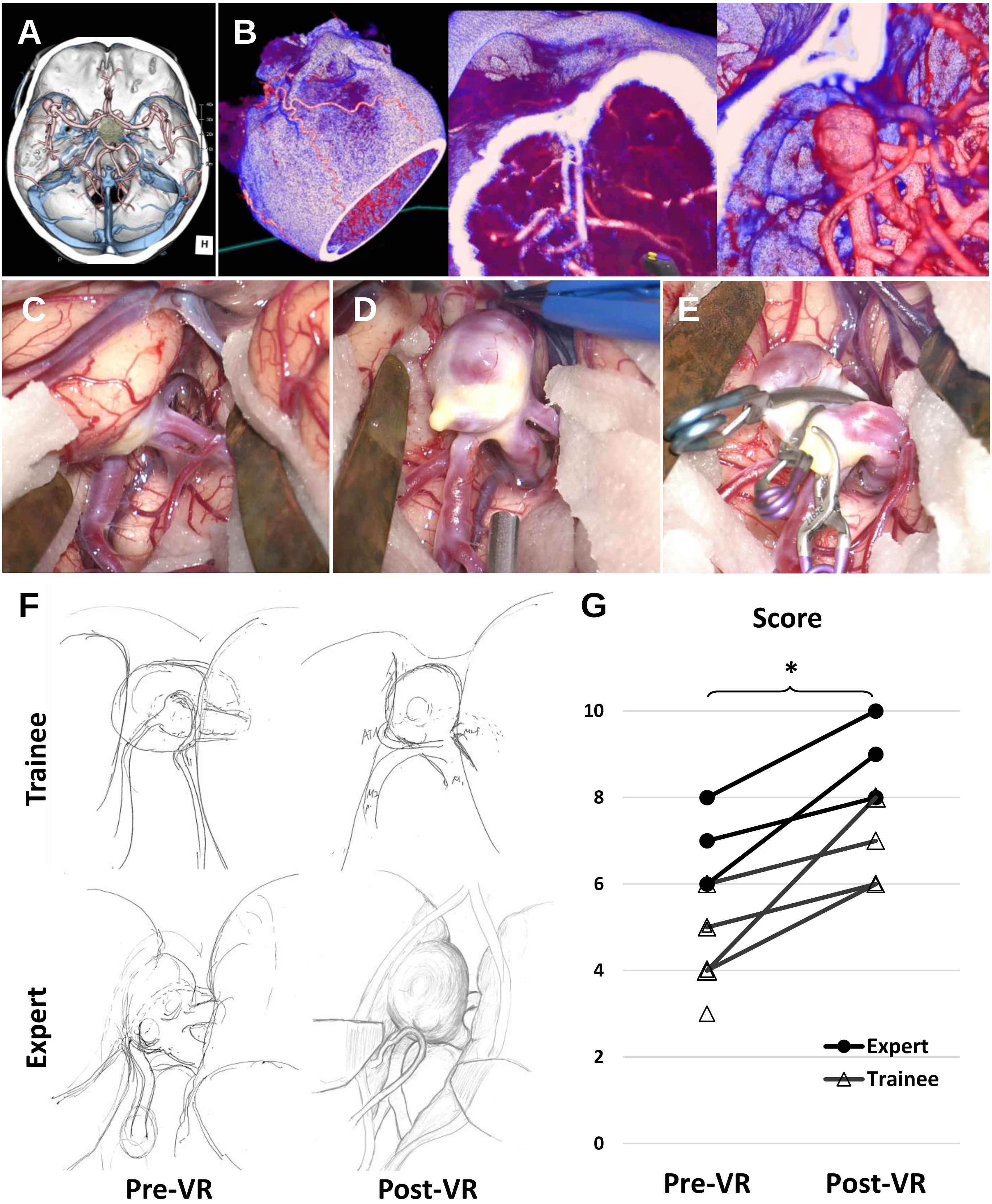

A
B
C
D
E
F
Trainee
Expert
Pre-VR
Post-VR
G
Score
*
10
8
6
4
2
0
Expert
Trainee
Pre-VR
Post-VR

Fig. 4

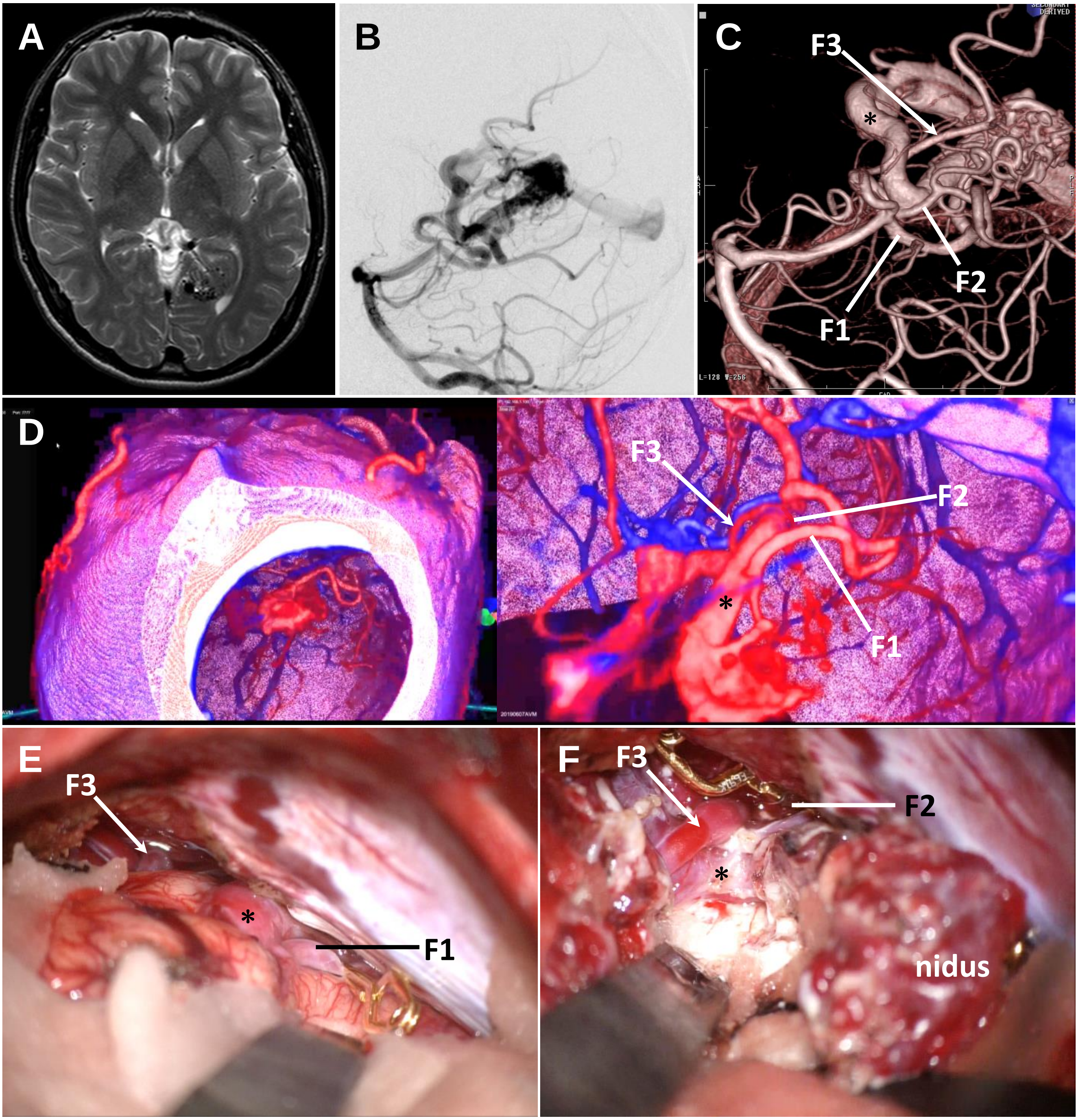

A
B
C
SECONDARY DERIVED
F3
*
F2
F1
L=128 W=256
D
F3
F2
*
F1
20190607AVM
E
F3
*
F1
F
F3
F2
*
nidus

Fig. 5

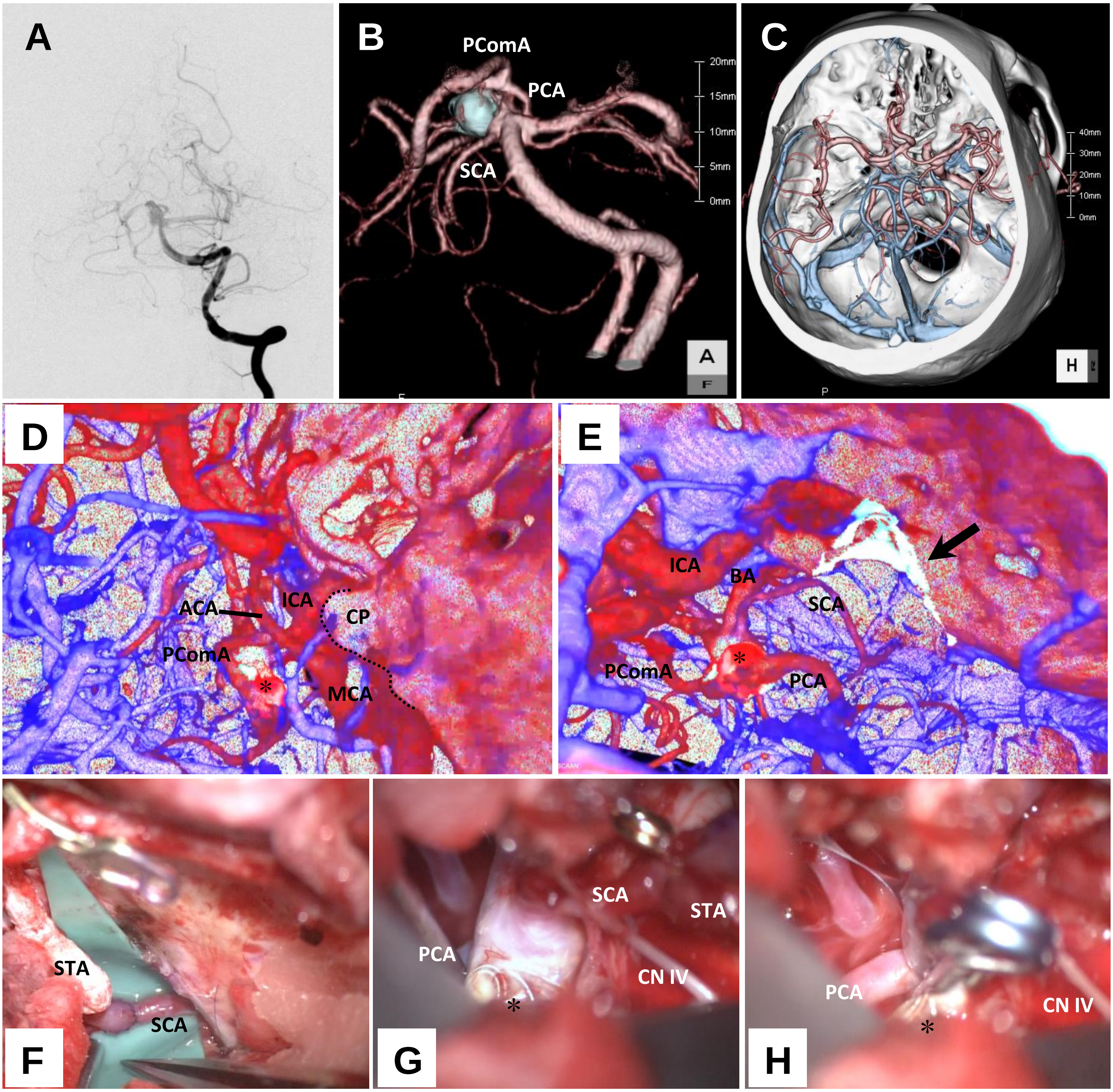

A
B
PComA
PCA
SCA
20mm
15mm
10mm
5mm
0mm
A
F
C
40mm
30mm
20mm
10mm
0mm
H
P
D
ACA
ICA
CP
PComA
*
MCA
E
ICA
BA
SCA
*
PComA
PCA
F
STA
SCA
G
SCA
STA
PCA
CN IV
*
H
PCA
CN IV
*

Fig. 6

Case No.	Age /sex	Disease	Location	Feature	Surgical plan	Results		Questionnaire		
						Surgery	Complication	Q1	Q2	Q3
1	71/F	AN	Rt. ICA-OpthA	Unrup./6 mm/superior proj.	Clipping via TSA with AC	Clipped as planned		4	4	3
2	62/M	AN	Rt. ICA-top	Unrup./5 mm/posterior proj.	Clipping via TSA	Coated d/t perforator adhesion		5	4	3
3	69/F	AN	Lt. ICA-top	Unrup. (growing)/4 mm/ posterior proj.	Clipping via TSA	Clipped as planned		4	4	3
4	76/F	AN	Lt. pMCA-ATA	Unrup. (growing)/4 mm/ inferior proj.	Clipping via TSA	Clipped as planned		4	3	3
5	67/F	AN	Lt. MCA	Unrup./9 mm/lateral proj.	Clipping via TSA	Clipped as planned		4	4	3
6	43/F	AN	Lt. MCA	Unrup. (growing)/4 mm/ antero-medial proj.	Clipping via TSA	Clipped as planned		4	3	3
7	67/F	AN	Rt. MCA	Unrup./4 mm/supero-lateral proj.	Clipping via TSA	Clipped as planned		5	4	3
8	41/F	AN	AComA	Unrup./4 mm/supero-posterior proj.	Clipping via IHA	Clipped as planned		5	4	3
9	70/M	Multiple ANs	Rt. MCA	Unrup./6 mm/inferior proj.	Clipping via rt. TSA	Clipped as planned		5	4	5
			Rt. ICA-AChoA	Unrup./5 mm/posterior proj.	Clipping via rt. TSA	Clipped as planned				
			AComA	Unrup./3 mm/supero-posterior proj.	Probably could not be clipped via rt. TSA	Could not be clipped				
			Lt. pACA	Unrup./2 mm/superior proj.	Probably could be clipped via rt. TSA	Clipped as expected				
10	66/M	AN	Lt. VA	Symptomatic/fusiform/thrombosed/34 mm	Trapping via LSA	Trapped as planned		5	3	4
11	62/M	AN	Rt. BA-SCA	Regrowth after coiling/10 mm/postero-lateral proj.	STA-SCA bypass + Clipping via SubT	Clipped as planned	Perforator injury (mRS;1)	5	5	5
12	58/M	AVM/dAVF	Lt. frontal	Post-embolization and radiation/S-M III/Borden III	Removal via frontal craniotomy	Removed as planned		3	3	3
13	30/M	AVM	Lt. temporal	Unrup. (seizure)/S-M IV	Removal via fronto-temporal craniotomy	Removed as planned		5	3	3
14	32/M	AVM	Rt. medial temporal	Ruptured/S-M III	Removal via TSA	Removed as planned	Perforator injury (mRS; 2)	4	4	4
15	22/M	AVM	Lt. parietal	Unrup./S-M III	Removal via parietal craniotomy	Removed as planned		5	5	3
16	26/M	AVM	Lt. parietal	Ruptured/S-M II	Removal via parietal craniotomy	Removed as planned		3	3	3
17	26/M	AVM	Lt. occipital	Unrup./S-M III	Removal via occipital craniotomy	Removed as planned	Infection	5	5	4
18	46/F	MMD	Lt. side	Hemorrhagic onset (contralateral side)/Suzuki IV	STA-MCA bypass + indirect bypass	Revascularized as planned		3	3	3

Table 1. Summary of patients included in the study

Abbreviation F; female, AN; aneurysm, Rt.; right, ICA; internal carotid artery, OpthA; ophthalmic artery, Unrup.; unruptured, proj.; projection, TSA; transsylvian approach, AC; anterior clinoidectomy, M; male, d/t; due to, pMCA: proximal middle cerebral artery, ATA; anterior temporal artery, MCA; middle cerebral artery, AComA; anterior communicating artery, IHA; interhemispheric approach, AChoA; anterior choroidal artery, pACA; proximal anterior cerebral artery, VA; vertebral artery, LSA; lateral suboccipital approach, BA; basilar artery, SCA; superior cerebellar artery, STA; superficial temporal artery, SubT; subtemporal approach, mRS; modified Rankin Scale, AVM; arteriovenous malformation, dAVF; dural arteriovenous fistula, S-M; Spetzler-Martin grade, Borden; Borden type, MMD; moyamoya disease, Suzuki; Suzuki stage