

HOKKAIDO UNIVERSITY

Title	Immersive 3-Dimensional Virtual Reality Modeling for Case-Specific Presurgical Discussions in Cerebrovascular Neurosurgery
Author(s)	Sugiyama, Taku; Clapp, Tod; Nelson, Jordan; Eitel, Chad; Motegi, Hiroaki; Nakayama, Naoki; Sasaki, Tsukasa; Tokairin, Kikutaro; Ito, Masaki; Kazumata, Ken; Houkin, Kiyohiro
Citation	Operative neurosurgery, 20(3), 289-299 https://doi.org/10.1093/ons/opaa335
Issue Date	2021-03
Doc URL	http://hdl.handle.net/2115/84221
Rights	This is a pre-copyedited, author-produced version of an article accepted for publication in Operative Neurosurgery following peer review. The version of record Taku Sugiyama, Tod Clapp, Jordan Nelson, BS, Chad Eitel, BS, Hiroaki Motegi, Naoki Nakayama, Tsukasa Sasaki, RT, Kikutaro Tokairin, Masaki Ito, Ken Kazumata, Kiyohiro Houkin, Immersive 3-Dimensional Virtual Reality Modeling for Case-Specific Presurgical Discussions in Cerebrovascular Neurosurgery, Operative Neurosurgery, Volume 20, Issue 3, March 2021, Pages 289–299 is available online at: https://doi.org/10.1093/ons/opaa335
Туре	article (author version)
Additional Information	There are other files related to this item in HUSCAP. Check the above URL.
File Information	Oper Neurosurg 20 289-299.pdf



1	Title: Immersive Three-Dimensional Virtual Reality Modeling for Case-Specific
2	Presurgical Discussions in Cerebrovascular Neurosurgery
3	
4	Taku Sugiyama, MD, PhD ¹⁾ , Tod Clapp, PhD ²⁾ , Jordan Nelson, BS ²⁾ , Chad Eitel, BS ²⁾ , Hiroaki
5	Motegi, MD, PhD ¹⁾ , Naoki Nakayama, MD, PhD ¹⁾ , Tsukasa Sasaki, RT ³⁾ , Kikutaro Tokairin, MD,
6	PhD ¹), Masaki Ito, MD, PhD ¹), Ken Kazumata, MD, PhD ¹), and Kiyohiro Houkin, MD, PhD ⁴)
7	
8	Affiliations:
9	1) Department of Neurosurgery, Hokkaido University Graduate School of Medicine, Sapporo, Japan
10	2) Department of Biomedical Sciences, Colorado State University, Colorado, USA
11	3) Department of Radiology, Hokkaido University Hospital, Sapporo, Japan
12	4) Department of Emergent Neurocognition, Faculty of Health Sciences, Hokkaido University,
13	Sapporo, Japan
14	
15	Correspondence: Taku Sugiyama, M.D., Ph.D.
16	Department of Neurosurgery, Hokkaido University Graduate School of Medicine, North 15 West 7,
17	Kita-ku, Sapporo 060-8638, Japan
18	Tel: +81-11-706-5987, Fax: +81-11-708-7737
19	E-mail: <u>takus1113@med.hokudai.ac.jp</u>
20	
21	Disclosure: The authors have no personal, financial, or institutional interest in any of the drugs,
22	materials, or devices described in this manuscript.
23	Sources of funding: None
24	Acknowledgements: We would like to thank Katsuhiko Hieda and Yoko Matsuura for their prominent
25	assistance of this study.

27 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, BananaVisionTM, 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' handdrawn 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.

46 *Conclusion:* Although rated as more useful by trainees than by experts, immersive 3D VR modeling 47 increased surgeons' understanding of patient-specific anatomy and improved surgical strategy in 48 certain cases involving challenging anatomy.

49

50 **Running Title:** Immersive VR for Cerebrovascular Surgery

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

 $\mathbf{2}$

53 Introduction

A precise understanding of microsurgical anatomy is essential for neurosurgeons. Surgical trainees spend years learning intricate neuroanatomy through case observations and conventional twodimensional (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.

59To 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 60 comprehensive 3D anatomical information to surgeons.²⁻⁴ Advanced simulation models have also been 61 combined with mixed reality technology.⁵ VR models require no extra cost to render models and allow 62the user to repeat sessions. Recent study confirmed that VR models have advantages over 3D-printed 63 models including the ability to zoom, greater image resolution, and greater model durability.³ Although 64 3D-printed models allow the use of depth perception and are easier to manipulate,³ "immersive" VR 65environments with modern head-mounted displays (HMDs) provide more convincing stereopsis than 66 stereoscopic viewing of 2D images, allowing the user to perceive depth in a similar way to 3D-printed 67 models.⁶⁻⁹ Gerig et al. have demonstrated that HMDs are superior to 2D screens in terms of depth 68 perception, regardless of additional artificially recreated depth cues.⁶ 69

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, BananaVisionTM (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.

77

79 Materials and methods

80 VR software (Video 1)

The VR modeling program BananaVisionTM 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**).

93

94 *Facility and surgeons*

The VR system utility for neurosurgery was independently assessed in Hokkaido University
Hospital. Two interconnected personal computers with the BananaVisionTM 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.

4

105 Study design

106 This study was approved by the institutional review board of Hokkaido University Hospital (No.

107 018-0291). Informed consent was obtained from all participants, including surgeons and patients.

108 The study design is summarized in **Figure 1B**.

All patients with cerebrovascular disease (CVD) scheduled or under consideration for 109 110 microsurgery between April 2019 and December 2019 were enrolled in this study. Patients with CVD 111 included patients with cerebral aneurysm, arteriovenous malformation (AVM), and occlusive CVD 112such as moyamoya disease (MMD). After the patients were admitted, staff surgeons and attending 113residents routinely discussed and created surgical plans using conventional imaging methods, 114 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 115116 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 117VR system. 118

119 Outcomes were evaluated 3–4 months after surgery. A favorable outcome was defined as a 120 modified Rankin Scale of either 0 or 1 or as neurological improvement after surgery relative to the 121 patient's preoperative state.^{11, 12}

122

123 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 patientspecific 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

 $\mathbf{5}$

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.

135

136 *Objective assessment of surgeons' anatomical understanding*

137To objectively evaluate whether the VR session improved surgeons' understanding of patient-specific 138anatomy, we evaluated presurgical schematic illustrations drawn by surgeons who had attended 139presurgical planning sessions. Presurgical illustrations were compared with the actual surgical videos, 140 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: 141142(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 143matter/tentorium) that was mainly attached to the aneurysm (0-2 points), (5) other anatomical 144145structures that were attached to the aneurysm (0 or 1 point), and (6) other anatomical structures in the 146 surgical view (0 or 1 point). The artistic element was not considered in this rating system. Information 147about when (pre- or post-VR) and by whom the presurgical illustration was drawn was blinded to the 148rater for evaluation purposes.

149

150 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 pvalue <0.05 was considered statistically significant.</p>

155

157 **Results**

158 *Patients' characteristics*

During the study period, 38 patients (15 aneurysms, 10 AVMs, and 13 occlusive CVDs) were 159160 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 161 162occlusive CVD who underwent extracranial-intracranial (EC-IC) bypass, VR sessions were not 163conducted because the manner in which EC-IC and indirect bypasses were performed was relatively 164 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 165166 was used during presurgical planning for the majority of aneurysm and AVM cases (75% and 70%, 167 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.

179

180 Effectiveness of presurgical VR sessions

181 Thirty-six responses to questionnaires were obtained from both primary and assistant surgeons across
182 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).

198

199 *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.

206

207 Illustrative cases

208 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**).

215

216 Case 11

217A 66-year-old male was admitted to the hospital with a rapidly regrowing BA-SCA aneurysm, which 218had previously ruptured and been coiled (Figure 6A–C). After discussing treatment options with the 219patient, surgeons decided to microsurgically repair the aneurysm. Although the distance between the 220intra-aneurysmal coils and the origin of posterior cerebral artery was sufficient to insert a clip, the 221distance between the coils and the origin of the SCA was significantly small to insert a clip without 222 sacrificing the SCA (Figure 6B). Therefore, surgeons planned to use clipping in conjunction with a 223superficial temporal artery (STA)-SCA bypass. Three surgical approach options were initially 224discussed: (1) a transsylvian approach, (2) a subtemporal approach, and (3) a subtemporal approach 225with an anterior petrosectomy. A VR session was subsequently conducted involving two experts and 226the attending residents. In the VR session, the surgeons determined that the retro-carotid space between 227the internal carotid artery and anterior clinoid was significantly narrow to use as a surgical corridor to 228the aneurysm in the transsylvian approach (Figure 6D). We also simulated a subtemporal approach 229combined with an anterior petrosectomy (Figure 6E); however, we determined that the space created 230by the anterior petrosectomy would not be beneficial to approach both the aneurysmal neck and the 231proximal BA. We therefore utilized a standard subtemporal approach and successfully accomplished 232both an STA-SCA bypass (Figure 6F) and clipping (Figure 6G, H).

233

235 **Discussion**

We prospectively tested the efficacy of a multiuser VR system during daily presurgical planning 236sessions for cerebrovascular surgeries. As a result, high utilization rates were observed before 237aneurysmal and AVM surgeries possibly due to the strengths of this system such as fast processing 238time and high usability.^{7, 8} Although the fundamental information volume was similar as the original 239CTA data,¹³ the surgeons could better understand patient-specific anatomy by observing 3D patient 240models in immersive VR space.¹⁴ As expected, the educational effect of VR was greater in the trainee 241group; however, even expert surgeons benefited from VR sessions. The multiuser functionality of the 242243system also enhanced presurgical planning and education because surgeons could discuss and teach surgical strategy while sharing the same surgical view in VR space.¹⁵ 244

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}

249

250 *Virtual models in cerebrovascular surgery*

Recent trends toward increased endovascular techniques and work-hour restrictions are decreasing the 251surgical experience of trainees and increasing the difficulty of surgery.^{18, 19} Presurgical simulation of 252patient-specific anatomy is therefore increasingly required for proper presurgical planning and 253education without threatening patients' safety. During aneurysm surgery, the most important strategic 254255objective is to secure the proximal parent artery while avoiding the risk of aneurysmal rupture. 256Therefore, information regarding the projection of the aneurysm and the spatial association between 257the 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 258also observed in AVM surgeries, specifically regarding the strategy for securing the main feeding artery 259while avoiding the occlusion of the passing artery and draining vein before nidus resection.²⁰ 260

261

262 *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 BananaVisionTM was likely its inability to fuse multimodal 268images. Several investigators have successfully built more realistic 3D graphics that include 269information regarding cranial nerves and the brain surface.^{21, 22} Another limitation is the current 270availability of other VR platforms.^{15, 23-25} Integrating VR systems with other devices such as navigation 271systems²⁶⁻²⁸ and augmented reality technologies²⁹⁻³¹ will likely produce the next generation of surgical 272planning tools. Additional technologies such as procedural simulation with haptic feedback and/or 273tissue deformation would also be another direction.^{23-25, 32} However, since these advanced systems will 274be expensive and time consuming, only disease- or purpose-specific usage of advanced technologies 275should be considered in the future.^{7, 33} 276

277

278 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 patientspecific anatomy and helped determine surgical strategy in certain cases involving complex and challenging anatomy.

284References 2851. Chan S, Conti F, Salisbury K, Blevins NH. Virtual reality simulation in neurosurgery: 286technologies and evolution. Neurosurgery. Jan 2013;72 Suppl 1:154-164. 2872. Tomlinson SB, Hendricks BK, Cohen-Gadol A. Immersive Three-Dimensional Modeling and 288Virtual Reality for Enhanced Visualization of Operative Neurosurgical Anatomy. World 289Neurosurg. Nov 2019;131:313-320. 2903. Bairamian D, Liu S, Eftekhar B. Virtual Reality Angiogram vs 3-Dimensional Printed 291Angiogram as an Educational tool-A Comparative Study. Neurosurgery. Aug 1 2019;85(2):E343-292E349. 2934. Randazzo M, Pisapia JM, Singh N, Thawani JP. 3D printing in neurosurgery: A systematic 294review. Surg Neurol Int. 2016;7(Suppl 33):S801-S809. 2955. Weinstock P, Rehder R, Prabhu SP, Forbes PW, Roussin CJ, Cohen AR. Creation of a novel 296simulator for minimally invasive neurosurgery: fusion of 3D printing and special effects. J297 Neurosurg Pediatr. Jul 2017;20(1):1-9. 2986. Gerig N, Mayo J, Baur K, Wittmann F, Riener R, Wolf P. Missing depth cues in virtual reality 299limit performance and quality of three dimensional reaching movements. PLoS One. 300 2018;13(1):e0189275. 3017. Kin T, Nakatomi H, Shono N, et al. Neurosurgical Virtual Reality Simulation for Brain Tumor 302Using High-definition Computer Graphics: A Review of the Literature. Neurol Med Chir (Tokyo). 303 Oct 15 2017;57(10):513-520. 304Li Y, Zhao Y, Zhang J, et al. Low-Cost Interactive Image-Based Virtual Endoscopy for the 8. 305 Diagnosis and Surgical Planning of Suprasellar Arachnoid Cysts. World Neurosurg. Apr 306 2016;88:76-82. 307 9. Mashiko T, Otani K, Kawano R, et al. Development of three-dimensional hollow elastic model for 308 cerebral aneurysm clipping simulation enabling rapid and low cost prototyping. World 309 Neurosurg. Mar 2015;83(3):351-361. 31010. Coburn JQ, Freeman I, Salmon JL. A Review of the Capabilities of Current Low-Cost Virtual 311Reality Technology and Its Potential to Enhance the Design Process. Journal of Computing and 312Information Science in Engineering. 2017;17(3). 31311. Sugiyama T, Nakayama N, Ushikoshi S, et al. Complication rate, cure rate, and long-term 314 outcomes of microsurgery for intracranial dural arteriovenous fistulae: a multicenter series and 315systematic review. Neurosurg Rev. Jan 2 2020. 31612. Darsaut TE, Findlay JM, Magro E, et al. Surgical clipping or endovascular coiling for unruptured 317 intracranial aneurysms: a pragmatic randomised trial. J Neurol Neurosurg Psychiatry. Aug 3182017;88(8):663-668. 319Stewart N, Lock G, Hopcraft A, Kanesarajah J, Coucher J. Stereoscopy in diagnostic radiology 13. 320 and procedure planning: does stereoscopic assessment of volume-rendered CT angiograms lead to

320 and procedure planning- does stereoscopic assessment of volume-rendered CT angiograms lead to 321 more accurate characterisation of cerebral aneurysms compared with traditional monoscopic 322 viewing? J Med Imaging Radiat Oncol. Apr 2014;58(2):172-182.

- Wake N, Wysock JS, Bjurlin MA, Chandarana H, Huang WC. "Pin the Tumor on the Kidney:" An
 Evaluation of How Surgeons Translate CT and MRI Data to 3D Models. Urology. Sep
 2019;131:255-261.
- 15. Kockro RA, Stadie A, Schwandt E, et al. A collaborative virtual reality environment for
 neurosurgical planning and training. *Neurosurgery*. Nov 2007;61(5 Suppl 2):379-391; discussion
 328 391.
- Sugiyama T, Lama S, Gan LS, Maddahi Y, Zareinia K, Sutherland GR. Forces of Tool-Tissue
 Interaction to Assess Surgical Skill Level. *JAMA Surg.* Mar 1 2018;153(3):234-242.
- 17. Sugiyama T, Nakamura T, Ito Y, et al. A Pilot Study on Measuring Tissue Motion During Carotid
 Surgery Using Video-Based Analyses for the Objective Assessment of Surgical Performance.
 World J Surg. Sep 2019;43(9):2309-2319.
- 18. Kalani MYS, Wanebo JE, Martirosyan NL, Nakaji P, Zabramski JM, Spetzler RF. A raised bar
 for aneurysm surgery in the endovascular era. *J Neurosurg.* May 2017;126(5):1731-1739.
- **19.** Quillin RC, 3rd, Cortez AR, Pritts TA, Hanseman DJ, Edwards MJ, Davis BR. Operative
 Variability Among Residents Has Increased Since Implementation of the 80-Hour Workweek. J
 Am Coll Surg. Jun 2016;222(6):1201-1210.
- Sugiyama T, Gan LS, Zareinia K, Lama S, Sutherland GR. Tool-Tissue Interaction Forces in
 Brain Arteriovenous Malformation Surgery. *World Neurosurg.* Jun 2017;102:221-228.
- 341 21. Oishi M, Fukuda M, Hiraishi T, Yajima N, Sato Y, Fujii Y. Interactive virtual simulation using a
 342 3D computer graphics model for microvascular decompression surgery. *J Neurosurg.* Sep
 343 2012;117(3):555-565.
- Kin T, Nakatomi H, Shojima M, et al. A new strategic neurosurgical planning tool for brainstem
 cavernous malformations using interactive computer graphics with multimodal fusion images. J
 Neurosurg. Jul 2012;117(1):78-88.
- 347 23. Alaraj A, Luciano CJ, Bailey DP, et al. Virtual reality cerebral aneurysm clipping simulation
 348 with real-time haptic feedback. *Neurosurgery.* Mar 2015;11 Suppl 2:52-58.
- 349 24. Gmeiner M, Dirnberger J, Fenz W, et al. Virtual Cerebral Aneurysm Clipping with Real-Time
 350 Haptic Force Feedback in Neurosurgical Education. *World Neurosurg.* Apr 2018;112:e313-e323.
- Wong GK, Zhu CX, Ahuja AT, Poon WS. Craniotomy and clipping of intracranial aneurysm in a
 stereoscopic virtual reality environment. *Neurosurgery*. Sep 2007;61(3):564-568; discussion 568 569.
- 354 26. Kockro RA, Reisch R, Serra L, Goh LC, Lee E, Stadie AT. Image-guided neurosurgery with 3355 dimensional multimodal imaging data on a stereoscopic monitor. *Neurosurgery.* Jan 2013;72
 356 Suppl 1:78-88.

Mert A, Buehler K, Sutherland GR, et al. Brain tumor surgery with 3-dimensional surface
 navigation. *Neurosurgery*. Dec 2012;71(2 Suppl Operative):ons286-294; discussion ons294-285.

359 28. Schulze F, Buhler K, Neubauer A, Kanitsar A, Holton L, Wolfsberger S. Intra-operative virtual

- 360 endoscopy for image guided endonasal transsphenoidal pituitary surgery. Int J Comput Assist
 361 Radiol Surg. Mar 2010;5(2):143-154.
- 362 29. Besharati Tabrizi L, Mahvash M. Augmented reality-guided neurosurgery: accuracy and
 363 intraoperative application of an image projection technique. *J Neurosurg.* Jul 2015;123(1):206364 211.
- 365 30. Incekara F, Smits M, Dirven C, Vincent A. Clinical Feasibility of a Wearable Mixed-Reality
 366 Device in Neurosurgery. *World Neurosurg*. Oct 2018;118:e422-e427.
- 367 31. Lovo EE, Quintana JC, Puebla MC, et al. A novel, inexpensive method of image coregistration for
 368 applications in image-guided surgery using augmented reality. *Neurosurgery.* Apr 2007;60(4
 369 Suppl 2):366-371; discussion 371-362.
- 370 32. Kockro RA, Killeen T, Ayyad A, et al. Aneurysm Surgery with Preoperative Three-Dimensional
 371 Planning in a Virtual Reality Environment: Technique and Outcome Analysis. *World Neurosurg.*372 Dec 2016;96:489-499.
- 373 33. McClelland TJ, Ford K, Dagash H, Lander A, Lakhoo K. Low-fidelity Paediatric Surgical
 374 Simulation: Description of Models in Low-Resource Settings. *World J Surg.* May 2019;43(5):1193375 1197.
- 376
- 377
- 378
- 379

- 380 Figure Legends
- 381 Fig. 1
- 382 A: Virtual reality (VR) station with BananaVisionTM installed together with hand controller and a
- 383 head-mounted display. Collaborative case discussions were conducted while sharing the same
- immersive VR models.
- 385 **B:** Study design.
- 386
- **Fig. 2** Flow chart of study participants during study period.
- 388 Abbreviations AN; aneurysm, AVM; arterio-venous malformation, AVF; arteriovenous fistula, CVD;
- 389 cerebrovascular disease, CTA; computed tomography angiography, MMD; moyamoya disease

- 391 Fig. 3
- 392 **A-C:** Bar graphs of primary surgeons' responses to the three questions for each case.
- 393 **D-F:** Bar graphs of the rates at which all surgeons answered "Strongly agree" or "Agree" to the three
- 394 questions. *p<0.05, **p<0.01.
- 395
- **Fig. 4** Presurgical schematic illustrations and scores (Case 5)
- 397 A: A conventional three-dimensional (3D) computed tomography angiogram (CTA).
- 398 **B:** A VR session. The users could view 3D models at any angle, simulate craniotomies, and experience
- 399 surgical approaches in immersive VR space.
- 400 **C-E:** Intraoperative photographs of the secured parent artery (**E**), the exposed aneurysm (**F**), and the 401 surgical site after clipping (**G**).
- 402 **F**, **G**: An example of presurgical illustrations before and after VR sessions. The scores tended to be
- 403 higher in experts than in trainees, and all scores increased after VR sessions. *p<0.05
- 404
- 405

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

407	An AVM was located in the left medial occipital lobe (A). A conventional digital subtraction
408	angiogram (DSA, B) and rotational DSA (C) showing three feeders and one drainer (asterisk). One
409	of the feeders $(F-2)$ was passing through the nidus and was supplying blood flow to normal brain
410	parenchyma. Through VR models, surgeons could experience an operative 3D view and understand
411	the spatial relationships between the nidus, drainer, and feeders (D). Intraoperative photographs
412	showing that the feeders and drainer were precisely identified (E), and the nidus was removed as
413	planned without injuring either the passing artery or drainer (F).
414	
415	Fig. 6 A case of a regrowing BA-SCA aneurysm after coiling (Case 11).
416	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 posteroinferior 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.

424 **Abbreviations** PComA; posterior communicating artery, PCA; posterior cerebral artery, SCA; 425 superior cerebellar artery, ACA; anterior cerebral artery, ICA; internal carotid artery, MCA; middle 426 cerebral artery, CP; clinoid process, BA; basilar artery, STA; superficial temporal artery, CN IV; fourth 427 nerve

428

430 Supplemental Digital Content

- **Supplementary Data 1** BananaVisionTM and image processing
- **Supplementary Data 2** A case of multiple aneurysms who selected for observation

435 Video Legends

Video 1 Multiuser immersive virtual reality system











В

Q2: Effectiveness in decision making on minor surgical procedure



Strongly Disagree Neutral Agree Strongly disagree agree



С

F

Q3: Effectiveness in decision making on critical surgical procedure



Strongly Disagree Neutral Agree Strongly disagree agree



Fig. 3







Fig. 4



Fig. 5



Fig. 6

Case Age No. /sex	Age	ge Disease	ise Location		Results		Questionnaire						
	/sex			Feature	Surgical plan	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			
	70/M	Multiple ANs	Rt. MCA	Unrup./6 mm/inferior proj.	Clipping via rt. TSA	Clipped as planned		_					
9			Multiple	Multiple	Multiple	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		5	4	5			
			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