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Original Article

Assessment of head-mounted display for exoscopic neurosurgery

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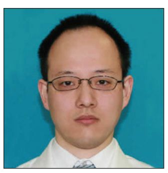

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ABSTRACT

Background: Head-mounted display (HMD) arises as an alternative display system for surgery. This study aimed to assess the utility of a stereoscopic HMD for exoscopic neurosurgery.

Methods: The leading operator and assistants were asked to assess the various aspects of the HMD characteristics compared to the monitor display using a visual analog scale (VAS)-based questionnaire. The VAS score ranged from 0 to 10 (0, HMD was significantly inferior to the monitor; 5, HMD and monitor display were equal; and 10, HMD was significantly superior to the monitor).

Results: The surgeons and assistants used and evaluated HMD in seven exoscopic surgeries: three tumor removal, one aneurysm clipping, one anterior cervical discectomy and fusion, and two cervical laminectomy surgeries. The leading operators' assessment of HMD-based surgery was not different from monitor-based surgery; however, the assistants evaluated the field of view, overall image quality, and the assisting procedure as better in MHD-based surgery than monitor-based surgery ($P = 0.039$, 0.045, and 0.013, respectively).

Conclusion: HMD-based exoscopic neurosurgery can be performed at a similar quality as monitor-based surgery. Surgical assistants may benefit from using HMD-based surgery.

Keywords: Exoscope, Head-mounted display, Questionnaire, Visual analog scale

INTRODUCTION

Monitor surgery using an exoscope has become more common in neurosurgery. While literature concerning the usefulness of the exoscope in neurosurgical operations is limited, its equivalence and superiority as an intraoperative and postoperative educational instrument are described in previous reports.[4,13-17,23] However, challenges persist in optimizing the intraoperative use of an exoscope due to factors such as the position of the leading operator, assistants, scrub nurses, and the three-dimensional 55-inch monitor providing the images from the exoscope.[4,13,17,21,23]

The head-mounted display (HMD) is a device worn on the head that presents images from an external instrument connected by cable. By displaying images in the user's line of sight, the

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HMD eliminates head or full-body motion limitations.[19,20,22] Advanced monitor surgery using an HMD with augmented reality (AR) or virtual reality (VR) is spreading in other departments.[19,25] This instrument has been applied in preoperative surgical simulation training or actual operations in orthopedics, ophthalmology, and neurosurgery.[1-3,6-8,14,21] VR using an HMD is utilized as a preoperative planning tool in thoracic and hepatic surgery, whereas AR using an HMD is utilized as a preoperative planning tool in dental surgery and neurosurgery (i.e., ventriculoperitoneal shunt).[18,24] In spine surgery, transforaminal epidural injection and insertion of pedicle screws have been performed with AR using an HMD.[10,12] However, the experience of utilizing AR and VR using an HMD seems limited to date. Although the monitors used in typical monitor surgery have limitations concerning their size, expense, and disposition in an operation room, HMDs have the advantage of not being restricted by monitor dimensions.

Therefore, the intraoperative use of an HMD with an exoscope can mitigate the disadvantages associated with the exoscope combined with a monitor. In actual practice, the functionality of the combination of an HMD and exoscope has been acknowledged as a preoperative training tool in clinical fields such as ophthalmology and orthopedics.[1,3,8] However, the intraoperative utility of an HMD combined with an exoscope in neurosurgery remains relatively unknown. Therefore, this preliminary study was designed to evaluate the utility of an HMD combined with an exoscope in neurosurgical operations, utilizing visual analog scale (VAS) scores.[9]

MATERIALS AND METHODS

All study participants provided informed consent. This study was approved by the ethical committee of the authors' institution (approval number: P 221000400).

Neurosurgeons wore an HMD (three-dimensional [3D] View Vision, FA. SYSTEM ENGINEERING CO., LTD., Nagoya, Japan) intraoperatively combined with an exoscope. The HMD weighed approximately 260 g, with a 3D resolution of 3840 × 1080 pixels. The HMD provides intraoperative images 2 m in front of the neurosurgeon's eyes, equivalent to those provided by a 57-inch monitor. The HMD is impermeable, and it displays side-by-side 3D images provided by an exoscope, right in front of surgeons' eyes. Therefore, unlike general head-up displays, surgeons do not observe surgical fields directly through the HMD, but rather surgical field images provided by an exoscope. The HMD has no AR functions to fuse intraoperative images with a navigation system or superimpose overlay images provided by several monitors. However, the HMD images provided by an exoscope in front of the surgeons' eyes overcome the disadvantages of the exoscope. The delay of an HMD's display is approximately 85 ms when wired and approximately 95–100 ms when not wired. The neurosurgeons' visual field was not completely sealed with this HMD device, allowing them to observe the surgical field directly by looking down. This feature allowed the neurosurgeons to exchange surgical instruments and control unexpected bleeding from the surgical field, similar to their experience using a surgical microscope.

In this study, we utilized the ORBEYE (Olympus, Tokyo, Japan) intraoperatively. The HMD was connected to the exoscope with a wire/wireless cable and showed 4K, 3D, magnified, and illuminated images of the surgical field provided by the exoscope in front of neurosurgeons [Figure 1]. The neurosurgeons continued using the HMD combined with the exoscope throughout the operation if they successfully achieved their surgical goals. However, if they opted to discontinue this combination intraoperatively, they completed the operation using the exoscope combined with a 3D 55-inch monitor.

Leading operators and assistants assessed the advantages and disadvantages of the HMD combined with an exoscope compared to those of the exoscope combined with a 3D 55-inch monitor. The leading operators and assistants had performed more than 50–100 surgeries with the exoscope combined with a 3D 55-inch monitor. Neurosurgeons assigned VAS scores to compare the utility of the HMD combined with the exoscope to that of the exoscope combined with a 3D 55-inch monitor. Scores >5 indicated that the neurosurgeon perceived superiority in the HMD and exoscope combination. A VAS score of 5 was defined as equivalent utility between the HMD with an exoscope and the exoscope combined with a 3D 55-inch monitor. Neurosurgeons also discussed the advantages and disadvantages of the HMD combined with the exoscope through interviews.

The leading operators and assistants answered a questionnaire to evaluate the utility of the HMD combined with the exoscope postoperatively. The questionnaire comprised ten questions [Figure 2], addressing aspects such as image resolution,

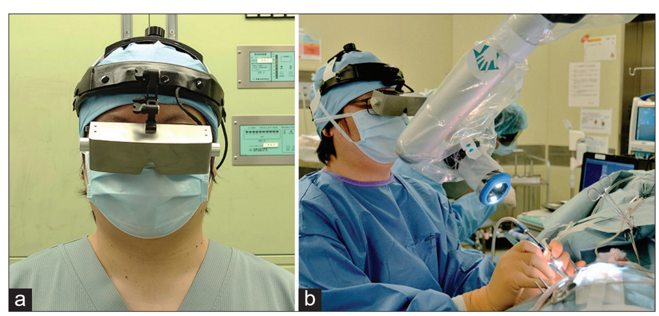

Figure 1: Representative image of using the head-mounted display. (a) The neurosurgeon puts on a head-mounted display before surgery. (b) The neurosurgeon operates using a head-mounted display combined with an exoscope.

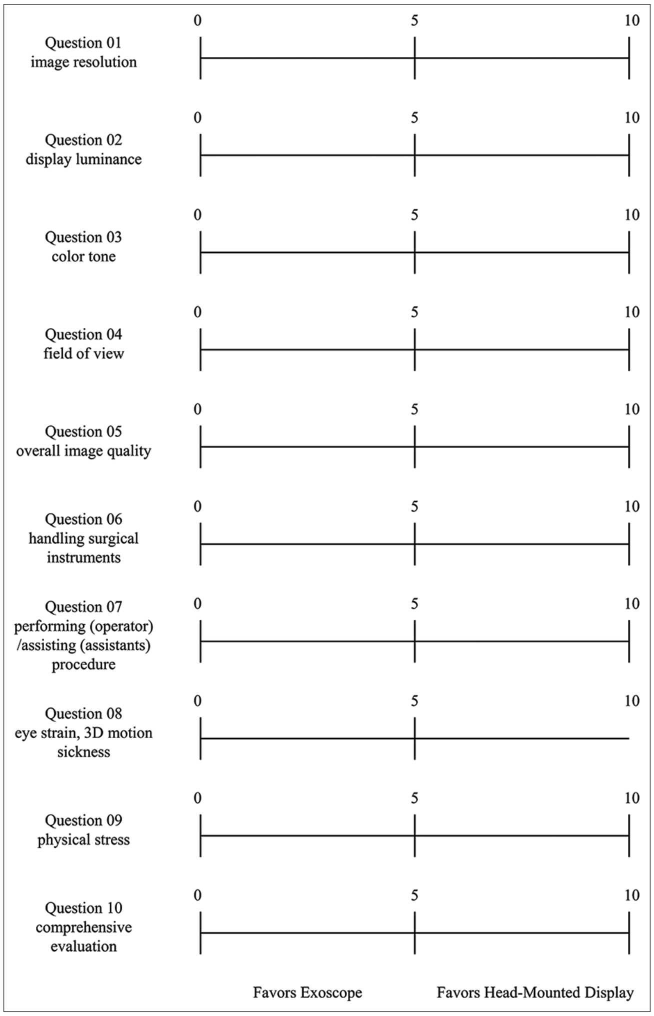

Figure 2: Questionnaire utilized in this study. The questionnaire consisted of ten questions. The neurosurgeons (leading operators and assistants) answered this questionnaire postoperatively, evaluating the utility of a head-mounted display combined with an exoscope compared to that of an exoscope combined with a three-dimensional 55-inch monitor.

display luminance, color tone, the field of view, overall image quality, handling surgical instruments, performing (operator)/assisting (assistants) procedure, eye strain, 3D motion sickness, physical stress, and a comprehensive evaluation. The questionnaire was created by four neurosurgeons who did not perform HMD-based exoscopic surgery. To prevent bias related to the questionnaire, the questions were designed to be simple. The questionnaire results from the surgeons and assistants were collected on the same day of surgery. The surgeons and assistants were instructed not to exchange information related to surgery using the HMD to avoid confounding factors.

The two-sample Student's *t*-test was used to evaluate the VAS scores related to the functionality and usability of the HMD. EZR was used for statistical analysis. Statistical significance was defined as $P < 0.05$.[11]

RESULTS

Surgery utilizing an HMD combined with an exoscope was used for seven patients (three women and four men; three tumor cases, one vascular case, and three spinal cases). In six of the seven cases, surgery was performed to completion with an HMD combined with an exoscope. The use of the HMD was intraoperatively suspended in one case due to surgeon discomfort related to lack of experience. All surgical procedures, from skin incision to wound closure, were performed under an HMD combined with an exoscope in the remaining six cases. Complete aneurysmal clipping was achieved in the vascular case, and total resection was achieved in all tumor cases.

No perioperative complications occurred [Table 1]. There were no significant differences in the leading operators' VAS scores concerning the utility of the HMD combined with the exoscope. Conversely, the VAS scores marked by the assistants showed a significant advantage of the HMD combined with the exoscope in Questions 4, 5, and 7 [Table 2]. Positive feedback on the luminance and visual field provided by the HMD was collected, while relatively negative comments pointed to the resolution of the images by the HMD, physical stress, and ease of exchange of surgical instruments during surgery with the HMD [Table 3]. No neurosurgeons reported intraoperative discomfort concerning the display delay time of the HMD, compared to the exoscope combined with a 3D 55-inch monitor.

HMD combined with an exoscope compared to exoscope with a 3D 55-inch monitor

When neurosurgeons used an exoscope combined with a 3D 55-inch monitor, the 3D 55-inch monitor had to be positioned in front of the leading operator. However, the position of the monitor was occasionally limited by the patients' intraoperative posture and the position of the exoscope. As a result, neurosurgeons experienced hand–eye discoordination. Meanwhile, when operating using the HMD combined with the exoscope, the leading operator did not need to rotate their head and posture to view the 3D 55-inch monitor by displaying the surgical field in front of the eyes. Therefore, the leading operator could easily coordinate their head and hand movements [Figure 3a and b]. The assistants could support the leading operator regardless of the position of the leading operator and monitors. The observers could also participate in the operation irrespective of the position of the monitors. Utilizing the HMD, the visual fields of the participants in the operation theatre were not interfered with [Figure 3c].

Table 1: Summary of the patients with a head-mounted display-assisted surgery.

Case	Sex	Age	Disease	Procedure	Outcomes	Complication	Discontinuing head-mounted display
#1	F	56	Convexity meningioma	Transcranial tumor removal	Excellent; total resection	None	Yes
#2	F	46	Anterior communicating artery aneurysm	Transsylvian approach and clipping of aneurysm	Excellent	None	No
#3	M	42	Glioblastoma multiforme	Transcranial tumor removal	Excellent; gross total resection	None	No
#4	M	82	Metastatic brain tumor	Transcranial tumor removal	Excellent; gross total resection	None	No
#5	M	55	Cervical disc herniation	Anterior cervical discectomy and fusion	Excellent	None	No
#6	F	64	Cervical canal stenosis	Cervical laminoplasty	Excellent	None	No
#7	M	59	Cervical canal stenosis	Cervical laminoplasty	Excellent	None	No

Table 2: Results of the postoperative questionnaire for the surgeons.

Questionnaire	Exoscope combined with a 3D monitor	HMD combined with an exoscope	
	Reference VAS score	Leading operators (*n*=7 cases)	
		VAS score	*P*-value*
Question 1: Image resolution	5	4.79±0.37	0.16
Question 2: Display luminance	5	6.70±2.29	0.073
Question 3: Color tone	5	4.62±0.64	0.145
Question 4: Field of view	5	6.21±2.36	0.199
Question 5: Overall image quality	5	4.63±0.68	0.176
Question 6: Handling surgical instruments	5	4.60±1.56	0.509
Question 7: Performing (operator)/assisting (assistants) procedure	5	5.31±1.22	0.512
Question 8: Eye strain, 3D motion sickness	5	4.66±2.02	0.668
Question 9: Physical stress	5	5.13±1.58	0.833
Question 10: Comprehensive evaluation	5	4.80±2.27	0.817
Questionnaire	**Reference VAS score**	**Assistants (*n*=5 cases)**	
		VAS score	***p*-value***
Question 1: Image resolution	5	7.88±2.94	0.06
Question 2: Display luminance	5	7.80±3.03	0.073
Question 3: Color tone	5	7.81±3.02	0.071
Question 4: Field of view	5	8.00±2.71	0.039
Question 5: Overall image quality	5	7.98±2.81	0.045
Question 6: Handling surgical instruments	5	3.28±4.17	0.367
Question 7: Performing (operator)/assisting (assistants) procedure	5	6.73±1.18	0.013
Question 8: Eye strain, 3D motion sickness	5	3.64±3.95	0.463
Question 9: Physical stress	5	7.15±2.12	0.053
Question 10: Comprehensive evaluation	5	6.34±1.35	0.058

HMD: Head-mounted display, VAS: Visual analog scale, *: Student's *t*-test

HMD in a spinal operation

When the exoscope combined with the 3D 55-inch monitor was used during spinal surgery, the assistants could not stand in front of the leading operator to avoid obstructing their view of the monitor. In addition, the monitor was frequently shifted to accommodate the leading operator's view. This situation resulted in hand–eye discoordination of the leading operator [Figure 4a and b]. However, when the HMD combined with the exoscope was utilized, the leading operator and assistants could operate regardless of the position of the monitor [Figure 4c and d].

Table 3: Postoperative comments on the surgeries performed using a head-mounted display.

Advantages	Disadvantages
• Better image luminance on the head-mounted display	• Surgeon's headache in the introductory period • Slightly lower image resolution • Scrub nurses' handling difficulties
• Prompt surgical field presentation on the eye-glass • Easy adjustment of surgical field centering • Easy head and hand coordination • No assistance-related visual interference	

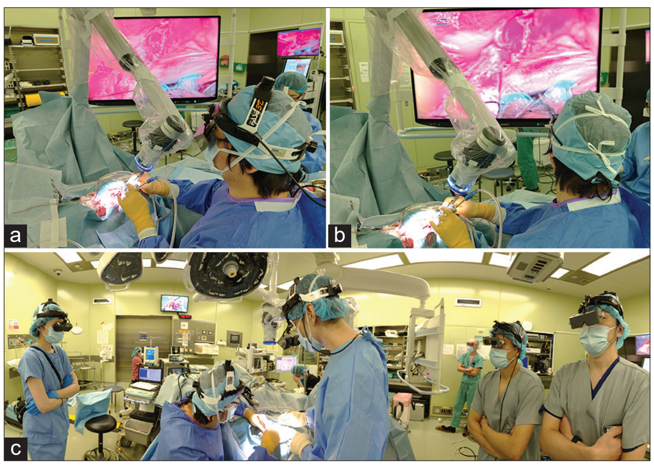

Figure 3: Intraoperative images when using head-mounted displays. (a, b) The neurosurgeon can coordinate their head and hand positions intraoperatively using a head-mounted display combined with an exoscope; meanwhile they cannot coordinate those positions without a head-mounted display. (c) The leading operator, assistant, and observer use their head-mounted displays. The position of the assistant using a head-mounted display cannot be limited by the positions of the leading operator or a monitor combined with an exoscope.

DISCUSSION

The superiority and equivalence of an exoscope combined with a 3D 55-inch monitor compared to a surgical microscope using a VAS score have been previously studied.[9] However, the utility of the intraoperative combination of an exoscope and an HMD has not been previously examined. In this preliminary study, we evaluated the usefulness of an HMD intraoperatively combined with an exoscope in neurosurgical operations compared to that of an exoscope combined with a 3D 55-inch monitor. The HMD was connected to the exoscope and provided images of the surgical field in front of the neurosurgeons' eyes. We used similar VAS scores to analyze the usefulness of this instrument combination, collecting the replies of the leading operators and assistants to the questionnaire. As statistical significance was not identified in most questions answered by the leading operators and assistants, the combination of an HMD and exoscope might be as valuable as that of an exoscope and a 3D 55-inch monitor. In addition, the results showed that an HMD combined with an exoscope, compared to an exoscope combined with a 3D 55-inch monitor, may provide superior visual field and image quality in neurosurgery. Importantly, our preliminary study showed that assistants considered the HMD combined with an exoscope to be superior to the exoscope with a 3D 55-inch monitor.

Statistical significance was detected in the VAS scores of the assistants replying to Question 4 (visual field), Question 5 (image quality), and Question 7 (ease of surgical procedure). This finding suggests that the visual field, image quality, and ease of surgical procedure might be superior in surgery under the HMD combined with the exoscope for assistants than with an exoscope and a 3D 55-inch monitor. To overcome the limitation of using an exoscope combined with a 3D 55-inch monitor, Takahashi *et al*. proposed presenting the actual surgical field images in the correct direction.[23] The HMD used in this study seems to present this solution.

Although statistical significance was not identified in the VAS scores for Question 8, eye strain and 3D motion sickness seem to result from the HMD combined with the exoscope compared to the exoscope combined with a 3D 55-inch monitor. These issues can be due to different device types, the field of view, time delay, frame rate, and flickering.[5] The visual field may be better with an HMD combined with an exoscope compared to an exoscope combined with a 3D 55-inch monitor (Question 4). In our preliminary study, the display delay time of the HMD did not result in intraoperative awkwardness. However, the intraoperative stress associated with the frame rate and flickering warrants further studies involving more cases and neurosurgeons.

Physical and visual fatigue and visually induced motion sickness related to the HMD have been described.[5] The weight of the HMD on the head and neck can gradually increase intraoperative stress.[5] Meanwhile, symptoms such as pain, tension, headache, irritation, dryness, tearing, and burning can manifest as visual fatigue.[5] The mismatch between the convergence distance of the eyes and the focal length, image distortion in the stereoscopic view, stress on the visual system while focusing the stereoscopic images, and proximity between the illumination source and the eyes are considered to be the causes of visual fatigue.[5] The conflicts among visual or vestibular input, proprioceptors, and motor information through limbs, and those in visual focus regulation can result in visually induced motion sickness.[5]

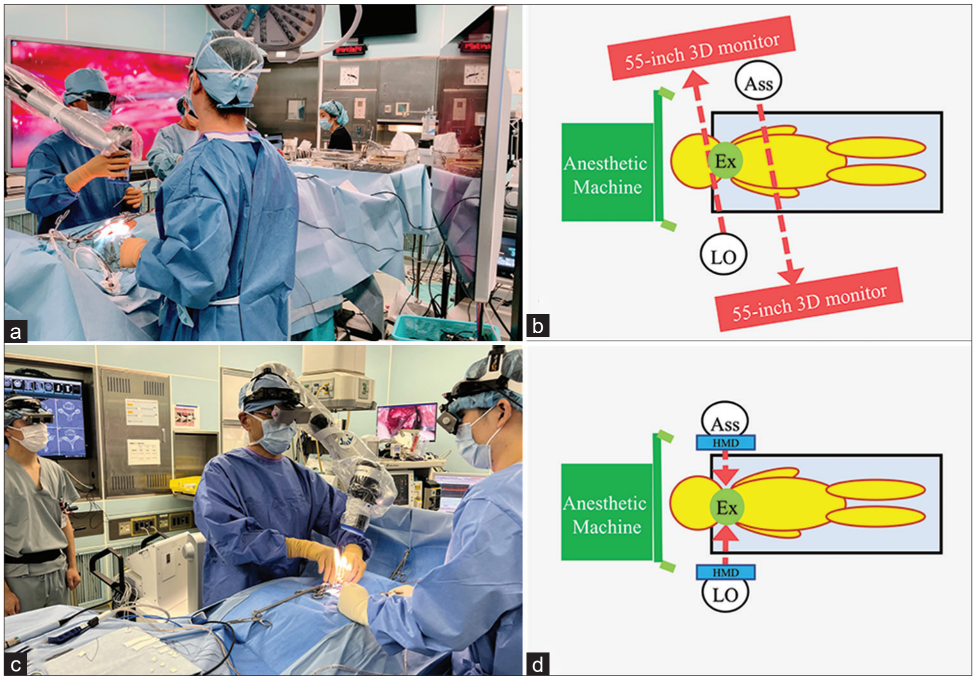

Figure 4: Position of the leading operator and assistant in spine surgery using an exoscope combined with three-dimensional 55-inch monitors (a and b) and head-mounted displays combined with an exoscope (c and d). (a) The leading operator and assistant must rotate and tilt their head and posture to view the monitors. (b) A schema of spine surgery using an exoscope combined with three-dimensional 55-inch monitors. (c) The leading operator and assistant do not have to rotate their head or posture to observe the surgical field visualized on their head-mounted displays. Hand–eye discoordination does not occur in this condition. (d) A schema of spine surgery using head-mounted displays combined with an exoscope (Ass: Assistant, Ex: Exoscope, HMD: Head-mounted display, LO: Leading operator).

In this study, one tumoral surgery was not completed using the HMD combined with the exoscope. In that case, the leading operator decided to suspend the combination of the HMD and the exoscope owing to intraoperative discomfort, with postoperative reports of pain and headache [Table 3]. These symptoms may be a disadvantage of the HMD.

As only limited cases with various diseases were enrolled in this study, further research is needed to determine whether it is worthwhile for neurosurgeons to use an HMD in various surgical scenarios. In this study, a neurosurgeon noted concerns about the image resolution of the HMD, specifically for bypass surgery. However, positive outcomes were reported in microvascular anastomosis performed with the combination of the HMD and exoscope.[3] Further, the discussion is warranted to identify which types of neurosurgical operations are most suitable for the HMD and exoscope.

Finally, introducing the HMD can cost several tens of thousands of dollars. However, because HMD may resolve the disadvantages of the exoscope for the main operator and assistants – such as intraoperative hand–eye discoordination and visual interference – its utility in terms of medical safety and assistant education should be factored in from the cost–benefit point of view.

Limitations

This study had some limitations. First, because this was a preliminary study in a single institute, the number of patients and neurosurgeons enrolled was limited. Due to this limitation, we did not evaluate the patient factors influencing the statistical results. Non-inferiority analysis was not conducted, and the patients managed in this study were diverse, including tumoral, vascular, and spinal cases. In addition, we did not collect objective data on the usefulness of the HMD concerning operation time and complications. No comparison was made between the image quality provided by the HMD combined with an exoscope and that of the exoscope with a 3D 55-inch monitor. This prompts a future investigation of the diseases that may be appropriately managed with the intraoperative use of an HMD combined with an exoscope. The operators and assistants had limited experience with surgery using an HMD combined with an exoscope compared to an exoscope with a 3D 55-inch monitor. Therefore, expectation or status quo bias may have been introduced while evaluating the usefulness of this combination. The learning curve of using an HMD combined with an exoscope was not discussed in this study and should also be of interest. In addition, the images provided by an exoscope are directly displayed on the HMD in front of surgeons' eyes, and the quality of intraoperative images from the HMD is judged individually by surgeons; therefore, it remains a limitation of this study that we could not evaluate intraoperative images from the HMD objectively or retrospectively. Finally, the HMD was not designed to be connected to an intraoperative navigation system. Hence, we could not evaluate the functionality of the HMD under an intraoperative navigation system.

CONCLUSION

Our study showed that using an HMD combined with an exoscope in neurosurgical surgery may be as helpful as using an exoscope combined with a 3D 55-inch monitor, and surgery with an HMD combined with an exoscope is not inferior to monitor-based surgery. This surgical method may also be less stressful for assistants compared with surgery managed with an exoscope combined with a 3D 55-inch monitor. In this regard, operations using an HMD may be educational. However, these findings are only preliminary and further research is warranted to validate our results.

Ethical approval

The research/study approved by the Institutional Review Board at the Department of Neurosurgery, Medical Research Institute KITANO HOSPITAL, PIIF Tazuke-Kofukai, number P221000400, dated October 17, 2022.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

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Nil.

Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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