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Augmented Reality in Stereotactic Neurosurgery: Current Status and Issues

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Abstract

Stereotactic neurosurgery is an established technique, but it has several limitations. In frame-based stereotaxy using a stereotactic frame, frame setting errors may decrease the accuracy of the procedure. Frameless stereotaxy using neuronavigation requires surgeons to shift their view from the surgical field to the navigation display and to advance the needle while assuming a physically uncomfortable position. To overcome these limitations, several researchers have applied augmented reality in stereotactic neurosurgery. Augmented reality enables surgeons to visualize the information regarding the target and preplanned trajectory superimposed over the actual surgical field. In frame-based stereotaxy, a researcher applies tablet computer-based augmented reality to check for the setting errors of the stereotactic frame, thereby improving the safety of the procedure. Several researchers have reported performing frameless stereotaxy guided by head-mounted-display-based augmented reality that enables surgeons to advance the needle at a more natural posture. These studies have shown that augmented reality can address the limitations of stereotactic neurosurgery. Conversely, they have also revealed the limited accuracy of current augmented reality systems for small targets, which indicates that further development of augmented reality systems is needed.

Keywords: augmented reality, neuronavigation, stereotactic neurosurgery

Introduction

The use of augmented reality (AR) in neurosurgery began to increase in the mid-2000s, and it has continued to increase since.[1)] Many researchers have applied AR in various neurosurgical procedures and have reported its usefulness.[2,3)] However, AR was not applied in stereotactic neurosurgery until 2019.[2)]

Stereotactic neurosurgery is an established technique with high accuracy and reliability. Recent progress in the accuracy and reliability of AR systems has led to the increased use of AR in stereotactic neurosurgery over the past several years.[4-7)] In this report, we review the feasibility of AR as a surgical support modality or as a distinct approach to stereotactic neurosurgery. Our previous study included in this report was approved by the Jichi Medical University Hospital clinical research ethics committee as a study on the "development and clinical application of AR neuronavigation" (ID B15-116 and 20-143). Written informed consent for study participation was obtained from all patients.

Augmented Reality in Neurosurgery and Its Features

AR technology supplements real-life visual information with virtual data. In most reports on AR applications in neurosurgery, AR was used as an AR neuronavigation (ARN) system, which superimposes three-dimensional (3D) virtual images of anatomical structures over the surgical field captured via electronic devices, such as video cameras, tablet computers, and head-mounted displays (HMD).[8-12)] Previous reports have identified two unique features of ARN.

First, ARN allows surgeons to use the navigation system in a more natural posture without shifting their view from

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the surgical field.[8,10,11,13-15] We have presented an image of a simulated surgery using HMD-based ARN as reported by Maruyama et al.[14] (Fig. 1), where the surgeon is performing the navigation-guided surgery without shifting from his surgical field view. Conventional neuronavigation forces the surgeon to assume an unnatural posture when using the navigation system and to shift views from the surgical field to the monitor.[8,10,12,15] Second, ARN can provide anatomical information using 3D virtual images.[8-16] We have also provided a screenshot of a tablet-based ARN-guided brain tumor surgery (Fig. 2). This ARN (trans-visible navigator) was developed and reported by Watanabe et al.[10] ARN superimposes 3D virtual images over the surgical field, enabling surgeons to easily integrate the anatomical information into the surgery. Conventional neuronavigation uses anatomical information obtained through computed tomography (CT) or magnetic resonance imaging. Thus, surgeons need to convert two-dimensional diagnostic images into 3D images.[8,10,13,15]

Researchers have applied ARN in various neurosurgical procedures, including brain tumor surgery, cerebrovascular surgery, ventriculostomy and neuroendoscopic surgery, spine surgery, and stereotactic radiosurgery, verifying these unique features of ARN that better support surgeons intraoperatively.[3,13,16-18] ARN has also been applied in surgical training, resident education, and patient education.[19,20]

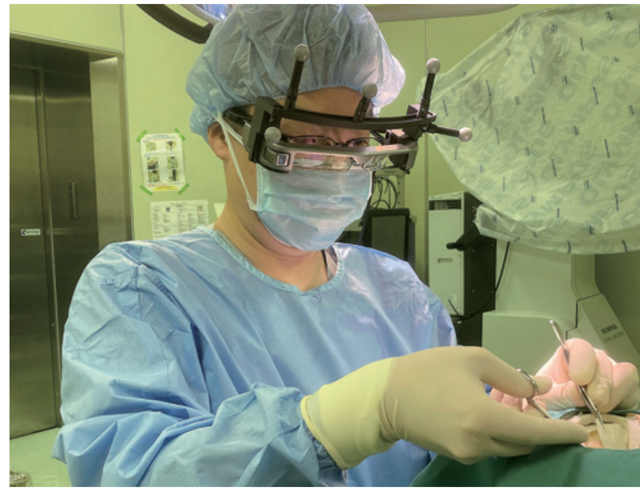

Fig. 1 Surgeon performing a simulated surgery using head-mounted-display-based augmented reality neuronavigation. The surgeon is performing the navigation-guided surgery in a natural posture without shifting from his view of the surgical field.

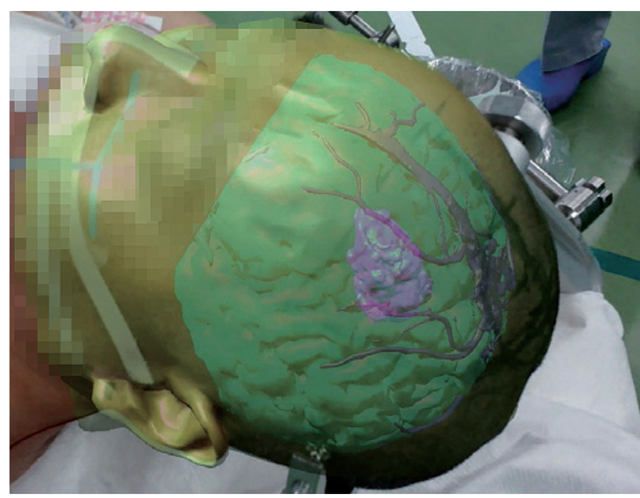

Fig. 2 Screenshot of an augmented reality neuronavigation-guided brain tumor surgery. Augmented reality neuronavigation superimposes three-dimensional virtual images over the surgical field, enabling surgeons to easily integrate the anatomical information into the surgery.

Augmented Reality in Frameless Stereotaxy

Frameless stereotaxy using conventional neuronavigation is an established method of stereotactic neurosurgery. However, it requires surgeons to shift views from the surgical field to the monitor and to advance the needle while assuming an uncomfortable position.[21-23] ARN is expected to overcome this limitation because it allows surgeons to operate the neuronavigation system at a more natural posture and without shifting views.

Gibby et al.[4] and Majak et al.[5] performed an HMD-based, ARN-guided, freehand brain biopsy on a cranial phantom to evaluate the feasibility of ARN. In these studies, HMDs were used to display the preplanned trajectory toward the target. Through the HMD, surgeons could view both the surgical field and the preplanned trajectory simultaneously without needing to shift views. Additionally, the surgeon could advance the needle in a more natural posture. These studies showed that frameless stereotaxy using ARN addressed the limitations of current frameless stereotaxy methods.

The accuracy error of the methods of the aforementioned studies was approximately 3 mm.[4,5] A meta-analysis by Fick et al.,[24] including five reports on ARN accuracy assessment, demonstrated that the accuracy error of ARN was approximately 2.5 mm. By adding the operator error of freehand puncture to the accuracy error of ARN, the 3-mm error of ARN-guided stereotaxy is explainable. This level of accuracy may be sufficient for ventriculostomy or biopsies of large lesions but not for small targets.[4] Further improvement of ARN is thus needed.

Skyrman et al.[6] evaluated frameless stereotactic brain biopsy guided by hybrid operating room-based ARN and reported an accuracy error of less than 1 mm for their ARN combined with a C-arm and cone-beam CT. Their report also uses a cranial phantom. Nevertheless, the application of their system in clinical systems is expected in the near future because of its sufficient accuracy for clinical use.

Augmented Reality in Frame-Based Stereotaxy

Frame-based stereotaxy using a stereotactic frame is an established approach in stereotactic neurosurgery. However, setting errors due to inaccurate registration, incorrect coordinates, and patient head movement while in the frame may decrease the accuracy of the procedure.[7,25,26] Moreover, once the setup is complete, a means of checking for setting errors has not been established.[7] It is, however, necessary to improve the safety of the procedure.

Previous studies have suggested that ARN is suitable for planning trajectories.[13,27] Observations can be made from the probe's eye view in ARN, allowing the surgeon to confirm the location of the trajectory within the target, as well as the absence of obstructions in the trajectory path (Fig. 3). Davidovic et al.[27] evaluated the advantages of ARN in trajectory planning through simulated surgery on a box with complex obstacles and targets placed inside. In this study, neurosurgeons guided using neuronavigation were tasked to reach a target while avoiding obstacles. Comparisons of the surgical invasiveness and time between conventional neuronavigation and ARN showed better results with ARN.

ARN, which is suitable for trajectory planning, may contribute to a checking system for the setting errors of the stereotactic frame. To verify the feasibility of ARN for setting-error checks, a study used a tablet-based ARN (trans-visible navigator) in CT-guided, frame-based stereotactic brain biopsy.[7] In this study, surgeons observed the trajectory set in the frame from the probe's eye view using the ARN before just a puncture. After the surgeon confirmed the setting trajectory pass within the lesion and absence of obstruction via important anatomical structures of the trajectory path, the surgeon advanced the needle. Five brain biopsies that applied this technique were performed without complications, indicating that ARN is feasible as a checking system for frame setting errors. However, ARN has limited accuracy. The accuracy error of the trans-visible navigator as evaluated in this study is 2.3 mm.[13] Hence, it is difficult to check setting errors within a few millimeters.

Summary

Currently, two research directions have been identified in the application of ARN in stereotactic neurosurgery. The first research direction is the evaluation of the feasibility of ARN-guided frameless stereotaxy.[4-6] ARN-guided stereotaxy for cranial phantoms showed that this procedure has the advantage of allowing the surgeon to advance the needle in a natural posture. The second research direction is the application of ARN in improving the safety of frame-based stereotaxy. ARN is suitable for trajectory planning and is thus equally suitable for checking for setting errors in frame-based stereotaxy.

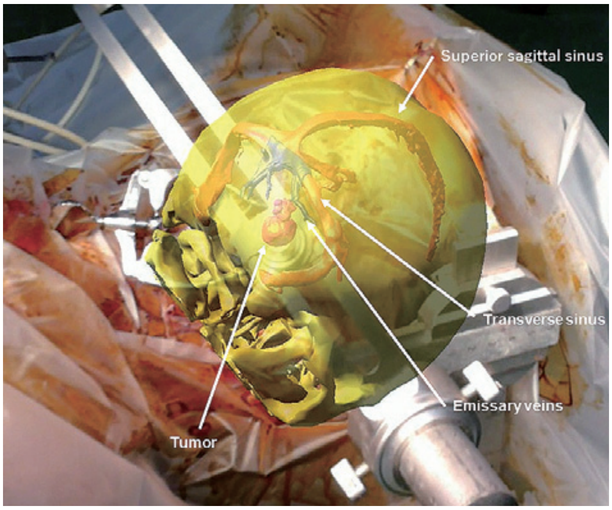

Fig. 3 Screenshot of the trans-visible navigator applied in a frame-based stereotactic brain biopsy for a cerebellar tumor. Observations can be made from the probe's eye view, allowing the surgeon to confirm the location of the trajectory within the tumor and the absence of obstruction by the venous sinus and emissary veins of the trajectory path.

In both research directions, the unique features of the ARN addressed the limitations of stereotactic neurosurgery. Moreover, ARN-guided or ARN-assisted stereotactic neurosurgery may be feasible for large targets. Nevertheless, for small targets, ARN has three issues that need to be addressed. The first issue is the accuracy of the ARN. Current ARN-guided or ARN-assisted stereotaxy has an accuracy error of 1-3 mm, which is insufficient for small targets. The second issue is clinical experience in the procedure. Most current reports on the application of ARN in stereotactic neurosurgery are cranial phantom-based studies. Further validation studies in the clinical setting are needed. The third issue is brain shift. Most ARN systems reported to date do not have the function to prevent accuracy loss due to brain shift.[28]

Conflicts of Interest Disclosure

All authors have registered their self-reported Conflict of Interest Disclosure Statement Forms on the Japan Neurosurgical Society website. The authors have no conflicts of interest to declare regarding the publication of this article.

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