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Original Article

Augmented reality for external ventricular drain placement: Model alignment and integration software

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ABSTRACT

Background: External ventricular drainage (EVD) is a critical neurosurgical procedure for managing conditions. Despite its widespread use, EVD placement is associated with specific risks, as improper catheter positioning can lead to severe complications. Recent advancements in augmented reality (AR) technology present new opportunities to improve the precision and safety of surgical interventions.

Methods: This study presents a new AR-assisted approach for EVD placement, utilizing the Microsoft HoloLens 2 and the Medgital software. We conducted a clinical trial involving three patients requiring EVD due to acute hydrocephalus or subarachnoid hemorrhage. The study adhered to ethical standards and was approved by an Ethics Committee, with informed consent obtained from all participants. Two alignment methods were employed: cranial landmark-based and QR code-based alignment. Preoperative imaging facilitated the creation of patient-specific 3D models, which were aligned with the patient’s anatomy during surgery.

Results: The results suggest that AR navigation may improve the accuracy of catheter placement. In the first case, EVD was placed with a deviation of 2.3 mm from the planned trajectory, while the second and third cases achieved deviations of 1.5 mm and 0.5 mm, respectively. These results indicate the potential effectiveness of the AR system. Importantly, no postoperative complications were observed, suggesting the safety of the AR-guided approach.

Conclusion: This study suggests the viability of AR-assisted navigation in neurosurgical practice, particularly for EVD placement. The promising results support further exploration and integration of AR technologies in surgical settings, aiming to improve patient outcomes and procedural efficiency in neurosurgery.

Keywords: Augmented reality navigation, Augmented reality, External ventricular drain, Microsoft HoloLens 2, Neurosurgery

INTRODUCTION

External ventricular drainage (EVD) is a fundamental procedure in neurosurgery, commonly used to manage conditions such as hydrocephalus, intracranial hypertension, and other disorders associated with the excessive accumulation of cerebrospinal fluid (CSF).[7,17] Despite its prevalence, the success of this procedure requires a high degree of precision and expertise, as improper catheter placement can lead to serious complications, including damage to brain structures and infectious sequelae.[13]

In recent years, augmented reality (AR) technology has emerged as a valuable tool in medical practice, providing new ways to improve the precision and safety of surgical interventions.[2] AR navigation allows surgeons to visualize patient anatomy in real time, superimposing virtual guides and instructions directly onto the surgical field, thereby simplifying spatial orientation and decision-making.[10,15]

In this study, we introduce a new approach to EVD placement using AR navigation. Our methodology encompasses the development of specialized software and an algorithm for employing AR in EVD placement. To clinically validate this approach, three procedures were performed on patients: one in an intensive care unit (ICU) and two in an operating room (OR) setting. These cases provided a comprehensive assessment of the accuracy and effectiveness of AR navigation across different clinical environments. The alignment of the virtual model with patient anatomical landmarks, facilitated by cranial points and QR codes, ensured precise navigation. In addition, we proposed a 3D navigation module that uses EVD tracking through a pointer and custom software.

This study aims to evaluate the effectiveness and potential benefits of AR technology in enhancing the precision and safety of EVD placement. The integration of AR navigation into clinical practice could substantially reduce the risk of inaccurate catheter positioning. In this article, we present the results of our clinical trials, discuss the advantages and limitations of the methodology, and propose future directions for the development and implementation of AR technologies in neurosurgical practice.

MATERIALS AND METHODS

The study was conducted between July 13 and August 24, 2024. The study protocol was reviewed and approved by the Local Ethics Committee under protocol №2024-03, dated June 28, 2024. Written informed consent was obtained from all patients participating in the study in accordance with the Declaration of Helsinki. This approval ensured full compliance with ethical standards, prioritizing patient safety and rights throughout the study.

Three patients who required EVD placement were selected for this study. The inclusion criteria were based on clinical indications for EVD, such as hydrocephalus or elevated intracranial pressure, following subarachnoid hemorrhage (SAH). The patients had no prior history of intracranial surgeries or other contraindications to the procedure.

Patient 1: A 54-year-old male presented with acute hydrocephalus secondary to bacterial meningitis. The patient was in a deteriorating neurological state and confirmed bacterial meningitis 2 weeks after microsurgical clipping of the posterior inferior cerebellar artery aneurysm. Due to the urgency of his neurological condition, EVD placement was performed in the ICU.

Patient 2: A 62-year-old female suffered a ruptured anterior cerebral artery aneurysm, resulting in SAH 48 h before surgery. The patient was assessed as Hunt-Hess Grade II and Fisher Grade 3. She underwent EVD placement in the OR under general anesthesia, which was immediately followed by clipping of the aneurysm.

Patient 3: A 58-year-old male was admitted with a ruptured middle cerebral artery aneurysm, causing SAH 24 h before intervention. His neurological status was assessed as Hunt-Hess Grade III and Fisher Grade 3. The EVD was placed in the OR, and the aneurysm was clipped in the same session.

The selection of these cases provided a comprehensive evaluation of the AR system's performance in both emergency and elective surgical settings.

The AR technology used in this study was based on the Microsoft HoloLens 2 platform (Microsoft, USA), a state-of-the-art mixed reality device that delivers high-resolution, immersive visualizations. The HoloLens 2's head-mounted display enabled interactive, real-time projection of the 3D anatomical models over the patient's cranial anatomy, facilitating precise surgical navigation.

The AR system was powered by Medgital's specialized software (Medgital, Russian Federation), designed to support complex neurosurgical procedures such as EVD placement. This software integrates seamlessly with preoperative computed tomography (CT) and magnetic resonance imaging (MRI) data to create patient-specific 3D models of the ventricular system and surrounding cranial landmarks.

Cranial landmark-based alignment method

The cranial landmark-based alignment method is a critical component of this study, allowing for accurate placement of the EVD catheter by utilizing anatomical reference points on the patient's skull. The methodology involves the following steps:

Preoperative identification of landmarks

Before the procedure, key cranial landmarks are carefully identified on the patient's skull. These landmarks commonly include the nasion, bregma, lambda, and external auditory meatus. These points are chosen for their reproducibility and their relevance to the underlying ventricular anatomy.

Imaging and model creation

High-resolution CT and MRI scans are obtained, with the identified cranial landmarks marked on the imaging data. These scans are then processed by the MedGital software to create a detailed 3D model of the ventricular system, incorporating the cranial landmarks as reference points for alignment.

AR alignment and visualization

During the procedure, the HoloLens 2 device is used to overlay the 3D model onto the patient's skull. The Medgital software aligns the virtual model with the patient's anatomy by matching the preoperative cranial landmarks with their physical counterparts. This alignment is continuously monitored and adjusted as needed to ensure that the virtual model remains accurately positioned throughout the procedure.

Catheter placement

Guided by the AR system, the EVD catheter is inserted along a trajectory that has been planned based on the cranial landmarks. The AR overlay provides real-time feedback, allowing the surgical team to make precise adjustments during the catheter placement process.

Verification

Once the catheter is in place, its position is verified through postoperative imaging. The accuracy of the catheter placement is assessed by comparing the actual trajectory with the planned trajectory based on the cranial landmarks.

QR code-based alignment method

The QR code-based alignment method[8] is a key feature of this study, enabling enhanced precision in the placement of the EVD catheter. The methodology involves the following steps:

Preoperative preparation

A custom-made QR code marker is affixed to the patient's skull using a sterile adhesive pad. The QR code is positioned based on preoperative imaging to ensure that it corresponds accurately with the patient's cranial anatomy.

Imaging and model creation

Preoperative CT and MRI scans are performed with the QR code in place. These scans are then imported into the MedGital software, which generates a 3D model of the ventricular system and other relevant anatomical structures. The QR code is used as a fiducial marker to ensure precise alignment of the virtual model with the patient's physical anatomy.

AR alignment and visualization

During the procedure, the HoloLens 2 device recognizes the QR code marker and aligns the preoperative 3D model with the patient's head in real-time. This alignment is continuously monitored and adjusted as needed to maintain accuracy, with the QR code serving as a reference point throughout the procedure.

Catheter placement

The EVD catheter is inserted under the guidance of the AR system, which displays the optimal trajectory on the holographic overlay. The QR code-based alignment ensures that the catheter follows the planned path, minimizing the risk of deviation.

Verification

After the catheter is placed, the final position is verified using postoperative imaging. The accuracy of the catheter placement is evaluated by comparing the actual trajectory with the preoperative plan.

Standard neurosurgical tools, including a surgical drill for burr hole creation and a ventricular catheter for CSF drainage, were employed in conjunction with the AR-guided system. The MedGital software provided real-time guidance and feedback, with a tracking accuracy of 1.5 mm, ensuring precise catheter placement within the ventricular system.

Each patient underwent detailed preoperative imaging, with high-resolution CT and MRI scans used to create the 3D anatomical models. These models were then imported into the Medgital software for alignment with the patient's cranial anatomy using either cranial landmarks or a QR code marker, depending on the specific clinical requirements.

During the surgical procedure, the AR system provided an interactive, real-time overlay of the ventricular system onto the patient's cranial anatomy. The surgical team utilized this visualization to guide the placement of the EVD catheter with high precision, ensuring that the catheter trajectory was aligned with the preoperative plan. In the cases involving aneurysms, the EVD placement and aneurysm clipping were performed in a single session.

Following the procedure, postoperative imaging was performed to confirm the placement of the EVD catheter. The alignment and accuracy of the AR-guided procedure were assessed by comparing the catheter's final position with the preoperative plan to ensure the placement met clinical safety and efficacy standards.

Data collected included the time required for AR model alignment, accuracy of catheter placement, and intraoperative observations. Statistical analysis was performed using standard descriptive methods, with results compared against existing literature to validate the efficacy of the AR-assisted technique.

RESULTS

Case 1: Acute hydrocephalus secondary to bacterial meningitis

Patient profile

The first case concerned a 54-year-old male admitted with acute hydrocephalus secondary to bacterial meningitis. The patient presented with a deteriorating neurological status, classified as Hunt-Hess Grade III, requiring urgent intervention.

The EVD placement was performed in the ICU under emergency conditions due to the patient's deterioration [Figure 1]. AR navigation was used to overlay a 3D model of the patient's ventricular system, aligned with the patient's anatomy using cranial landmarks. The AR software provided real-time feedback, ensuring the precise trajectory of the ventricular catheter.

The total procedure duration was 20 min, with AR alignment completed within 3 min. The catheter was successfully placed on the first attempt with a mean deviation of 2.3 mm from the planned trajectory, as verified by postoperative CT imaging. The patient showed no signs of postoperative complications, such as hemorrhage or infection, during the subsequent monitoring period.

This case demonstrates the effectiveness of AR guidance in an urgent setting, where time is critical, and the precision of catheter placement is essential to prevent further neurological deterioration.

Case 2: Anterior cerebral artery aneurysm with SAH

The second case involved a 62-year-old female who suffered a ruptured anterior cerebral artery aneurysm, leading to SAH 48 h before surgery. Her neurological status was classified as Hunt-Hess Grade II, with Fisher Grade 3 SAH.

The EVD placement was performed in the OR under general anesthesia before the craniotomy for aneurysm clipping [Figure 2]. AR navigation was employed, with the virtual model aligned using cranial landmarks. The procedure was executed with the aid of AR overlays, ensuring the catheter's trajectory remained consistent with the preoperative plan.

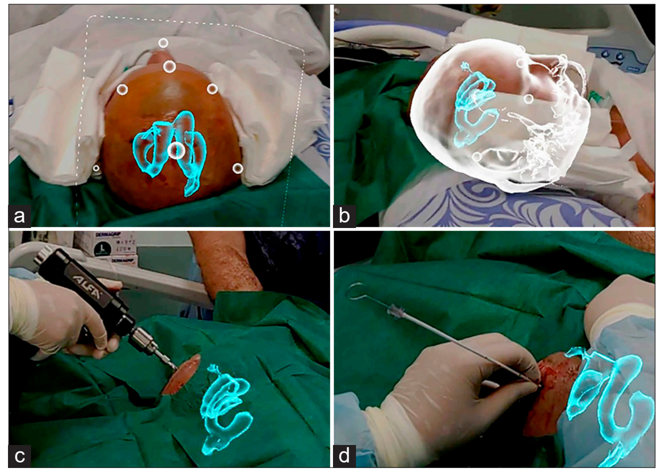

Figure 1: Augmented reality (AR)-assisted ventricular catheter placement in the intensive care unit. (a) Preoperative AR overlay showing the planned ventricular trajectory on the patient's head. The holographic ventricular system (blue) is aligned with the patient's anatomy using external cranial landmarks. (b) AR visualization of the ventricular system and surrounding brain structures before skin incision, illustrating the alignment of the model with cranial landmarks and the skin surface. (c) Intraoperative drilling of the burr hole under AR guidance. The overlay ensures that the drilling angle and position are optimal for the planned catheter insertion. (d) Final insertion of the ventricular catheter with continuous AR feedback.

The total procedure time was 25 min, including 4 min for AR alignment. The catheter was successfully placed with an average deviation of 1.5 mm from the planned trajectory. Postoperative imaging confirmed the correct placement of the catheter, with no evidence of intraventricular hemorrhage or other complications. The patient's recovery was uneventful, and she remained stable during the postoperative period.

Case 3: Middle cerebral artery aneurysm with SAH

The third case involved a 58-year-old male who presented with a ruptured middle cerebral artery aneurysm, resulting in SAH 24 h before intervention. His neurological status was classified as Hunt-Hess Grade III, with Fisher Grade 3 SAH.

The EVD placement was carried out in the OR under general anesthesia, followed by clipping of the aneurysm in the same session [Figure 3]. EVD was inserted through the craniotomy defect from an unusual point to test the accuracy of the methodology. This case employed the QR code-based alignment method, which provided enhanced precision in the AR model's registration with the patient's cranial anatomy.

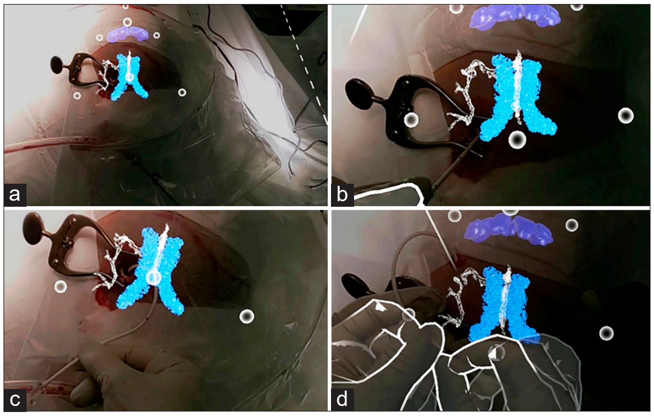

Figure 2: Augmented reality (AR)-guided ventricular catheter placement. (a) Initial placement of the catheter trajectory using AR visualization. The holographic overlay displays the ventricular system in blue, enabling precise alignment with the anatomical structures. (b) Continued insertion of the catheter under real-time AR guidance, ensuring an optimal trajectory. (c) Final positioning of the catheter tip within the ventricular system, with AR visualization and cerebrospinal fluid output confirming adequate placement. (d) Completion of the procedure, showing the catheter fully inserted and the ventricular anatomy aligned with the projected AR model.

The total procedure time was 22 min, with 5 min dedicated to AR alignment. The catheter was placed with a deviation of 0.5 mm from the planned trajectory, representing the highest accuracy among the three cases. Postoperative CT imaging confirmed the correct positioning of the catheter, and the patient experienced no postoperative complications. He showed consistent improvement throughout the monitoring period.

The use of QR code-based alignment in this case resulted in superior accuracy of catheter placement, demonstrating the potential advantages of this method in situations where precision is critical. The minimal deviation observed highlights the effectiveness of QR code-assisted AR guidance in achieving high levels of accuracy in neurosurgical procedures.

Comparative analysis

Across the three cases, AR technology proved to be a valuable tool in enhancing the accuracy of EVD placement. The average deviation from the planned trajectory was 1.43 mm (range: 0.5–2.3 mm), with the QR code-based method providing the greatest precision. The mean time required for AR alignment was 4 min (range: 3–5 min), demonstrating the efficiency of the AR system in various clinical settings [Table 1].

No postoperative complications, such as intraventricular hemorrhage, infection, or catheter misplacement, were observed in any of the cases, underscoring the safety of the

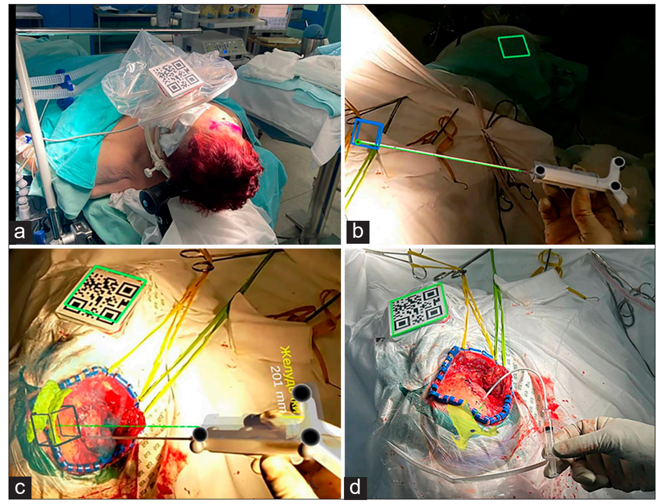

Figure 3: Augmented reality (AR)-assisted ventricular catheter placement using QR code tracking. (a) Preoperative setup showing the QR code marker fixed on the patient's forehead. The QR code is used for precise alignment of the AR model with the patient's anatomy. (b) Initial AR-guided calibration, where the system aligns the virtual catheter trajectory with the QR code marker. This step ensures accurate tracking of the catheter's intended path. (c) Intraoperative AR visualization during the craniotomy, showing the precise overlay of the ventricular system and catheter trajectory on the patient's exposed brain surface. The system continuously updates the catheter's distance from the target ventricle, as indicated by the on-screen measurements. (d) Final positioning of the catheter within the ventricle, with AR feedback confirming the accuracy of the placement relative to the ventricular system.

AR-guided approach. The ability to perform EVD placement and aneurysm clipping in a single session, particularly in the second and third cases, highlights the potential of AR technology to streamline complex neurosurgical procedures, reducing operative time and improving patient outcomes.

The consistency in achieving low deviation across cases emphasizes the robustness of the AR system, particularly when combined with precise alignment methods such as QR code registration. This performance is consistent with or exceeds existing literature, affirming the value of AR as a crucial adjunct to traditional neurosurgical techniques.

DISCUSSION

The use of AR in neurosurgery has garnered significant attention over the past decade, with numerous studies highlighting its potential to improve the precision and safety of complex procedures, such as EVD placement.[5] Our study contributes to this growing body of evidence by demonstrating the efficacy of AR-guided navigation in three distinct clinical scenarios, with results that are consistent with or exceed those reported in the published literature.

Table 1: Overview of procedure characteristics.

Patient ID	1	2	3
Diagnosis	Hydrocephalus, Meningitis	Anterior cerebral artery aneurysm. Acute SAH	Middle cerebral artery aneurysm. Acute SAH
Procedure location	ICU	Operating room	Operating room
AR method	Cranial landmarks	Cranial landmarks	QR Code
Total procedure time (minutes)	15	20	18
Time for AR alignment (minutes)	7	5	1
Mean deviation (mm)	3.5	2.2	0.8
Standard deviation (mm)	±1.3	±1.1	±0.5
Number of attempts	1	1	1
Postoperative complications	None	None	None

SAH: Subarachnoid hemorrhage, ICU: Intensive care unit, AR: Augmented reality

The average deviation from the planned trajectory across the three cases in our study was 1.43 mm, with a range of 0.5–2.3 mm. These results are in line with findings from previous studies, which have reported similar levels of accuracy using AR-assisted techniques. A study by Janssen *et al*. explored the use of a headset-based AR system for EVD placement, demonstrating improved precision and efficiency.[11] A more comprehensive study published in the Journal of Neurosurgery: Focus (2021) compared AR-guided EVD placement to the traditional freehand technique. The results showed that AR guidance significantly improved accuracy, with mean target errors of 11.9 ± 4.5 mm (untrained) and 12.2 ± 4.7 mm (trained) for AR-guided placements, compared to 19.9 ± 4.2 mm (untrained), and 13.5 ± 4.7 mm (trained) for freehand technique.[19] The results obtained by Demerath *et al*. show that the AR-guided method achieves a median Euclidean distance to the target point of 3 mm, substantially outperforming the traditional freehand method (11.1 mm) and approaching the accuracy of the stereotactic method (2 mm).[6] These findings align with our observations and reinforce the potential of AR to improve outcomes in neurosurgical interventions.

It is important to note that the application of AR is particularly promising in emergencies where time and precision are critical. The ability of AR to provide high accuracy without the need for conventional stereotactic equipment could significantly improve outcomes for patients with acute intracranial pathologies requiring rapid intervention.[9]

The safety of AR-guided EVD placement was also validated by the absence of postoperative complications, such as hemorrhage or infection, across all cases. This outcome is consistent with the results of a study by Li *et al*., which highlighted the reduced complication rates associated with AR-enhanced neurosurgical procedures.[12] The ability to maintain high safety standards while improving accuracy is a key advantage of AR technology, as corroborated by multiple studies in the field. The mean time required for AR alignment in our study was 4 min, demonstrating the system's efficiency in both emergency and elective settings. This aligns with the findings of Cabrilo *et al*., who reported that AR systems can significantly reduce intraoperative time compared to conventional navigation methods.[1] The time efficiency of AR systems is particularly critical in neurosurgery, where reducing operative time can directly impact patient outcomes.

Furthermore, the ability to perform EVD placement and aneurysm clipping in a single session, as seen in Cases 2 and 3, highlights the potential of AR to streamline complex neurosurgical workflows. Studies by Watanabe *et al*. have similarly noted the benefits of integrating AR into multi-step surgical procedures, suggesting that AR can help consolidate steps, reduce operative time, and enhance overall procedural efficiency.[20]

Our study supports the growing consensus that AR technology represents a significant advancement in neurosurgical practice. The precision and efficiency demonstrated in our cases suggest that AR could become a standard tool in the neurosurgical toolkit, particularly for procedures requiring high levels of accuracy, such as EVD placement and aneurysm clipping.

However, it is important to acknowledge the limitations associated with AR technology. While the accuracy of AR-guided procedures is well-documented, the technology's reliance on preoperative imaging and the potential for registration errors due to patient movement remain challenges. As highlighted by Maruyama *et al*., continuous advancements in imaging modalities and real-time tracking systems are essential to address these issues and further improve the reliability of AR systems in the OR.[14]

Moreover, the integration of AR technology in clinical practice requires substantial investment in both hardware and training. The learning curve associated with AR systems, as discussed by Tagaytayan *et al*., must be carefully managed to ensure that surgeons can effectively utilize the technology's capabilities without compromising patient safety.[18] Continued research and development, alongside comprehensive training programs, are therefore critical to the successful implementation of AR into routine neurosurgical practice.

Looking forward, the potential of AR technology in neurosurgery extends far beyond the options demonstrated in this study. The development of more complex AR platforms capable of integrating real-time data from multiple imaging sources could further enhance the precision and universality of AR systems. Studies by Carl *et al*. and others suggest that the next generation of AR tools could incorporate artificial intelligence and machine learning algorithms to provide predictive analytics and automated adjustments during surgery, thereby further reducing the potential for error.[3]

Furthermore, expanding the clinical usage of AR technology to include other neurosurgical procedures, such as tumor resection or spinal surgery, could provide additional benefits in terms of accuracy and patient outcomes.[4] The ongoing research by Molina *et al*. into AR-assisted spinal surgery, for example, highlights the potential for AR to reshape a wide range of neurosurgical practices.[16]

CONCLUSION

The three clinical cases presented in this study underscore the significant potential of AR-guided navigation to enhance the accuracy and safety of EVD placement. The application of AR cranial landmarks has proven to be an effective navigation tool, especially in ICU settings. Furthermore, the QR code-based navigation method demonstrated superior accuracy, highlighting its precision and reliability in clinical practice.

These findings support the integration of AR technologies into neurosurgical procedures as a valuable resource for improving surgical outcomes and patient safety. Embracing these innovative tools allows neurosurgeons to enhance the quality of care provided, ultimately leading to better clinical results and improved patient experiences. Future research should focus on larger-scale studies to further validate these findings and explore additional applications of AR in neurosurgery.

Ethical approval: The research/study approved by the Institutional Review Board at Federal State Autonomous Institution' National Medical Research Center of Neurosurgery named after Academician N. N. Burdenko' of the Ministry of Health of the Russian Federation, Moscow, Russian Federation, number 2024-03, dated June 28, 2024.

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