**Review Article**

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# Extended Reality in Neurosurgery : Surgical Planning, Navigation, Education, and Patient Communication

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Extended reality (XR), encompassing virtual reality, augmented reality (AR), and mixed reality, has emerged as a transformative technology in neurosurgery. This narrative review examines the current applications of XR technologies across four major domains : surgical planning and visualization, intraoperative navigation, medical education and training, and patient/caregiver communication. The integration of artificial intelligence-based lesion segmentation with XR platforms has enabled precise three-dimensional visualization of complex intracranial pathologies. Modern AR navigation systems, utilizing both optical see-through and video see-through head-mounted displays, have demonstrated submillimeter accuracy in recent clinical studies. Educational applications of XR have shown significant improvements in anatomical understanding and surgical skill acquisition among neurosurgery trainees. Furthermore, XR-enhanced patient communication tools have improved comprehension of complex neurosurgical procedures and informed consent quality. Despite current limitations including hardware constraints, workflow integration challenges, and the need for larger validation studies, XR technologies hold substantial promise for advancing pediatric neurosurgical care. This review provides a critical analysis of current evidence, discusses the advantages and limitations of different XR modalities, and offers perspectives on future developments in this rapidly evolving field.

**Key Words :** Augmented reality · Virtual reality · Neurosurgery · Pediatrics · Artificial intelligence · Patient education.

## INTRODUCTION

Extended reality (XR) encompasses virtual reality (VR), augmented reality (AR), and mixed reality (MR). In VR, users are immersed in a computer-generated environment, while AR overlays digital information onto the real world, and MR allows interaction between virtual and physical objects. These technologies have evolved from entertainment to sophisticated medical tools, with neurosurgery emerging as a promising field for clinical implementation[3,26].

Pediatric neurosurgery presents unique challenges that make XR technologies particularly valuable. Children's neuroanatomy demonstrates significant variation during development, pathologies often occur in eloquent brain regions, and the small operative fields demand exceptional precision[7]. Furthermore, explaining complex surgical procedures to young patients and their families requires innovative communication approaches. Traditional neuronavigation systems, while valuable, have limitations including the need for continuous visual attention shifts between the surgical field and display monitors, potential regis-

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tration errors, and difficulties in conveying three-dimensional spatial relationships[31].

The convergence of artificial intelligence (AI) with XR technologies has opened new possibilities for pediatric neurosurgery. Deep learning algorithms can now automatically segment brain lesions, tumors, and critical structures from multimodal imaging data, providing the foundational data for XR visualization. Among available frameworks, self-configuring neural networks such as nnU-Net have achieved state-of-the-art performance in brain tumor segmentation, enabling accurate three-dimensional reconstructions that can be integrated into XR surgical planning platforms[25].

This narrative review aims to provide an analysis of XR applications in pediatric neurosurgery, focusing on four major domains : AI-based lesion segmentation and visualization, XR-assisted surgical navigation, medical education and training, and patient communication. We critically examine current evidence, discuss the advantages and limitations of different XR modalities including optical see-through (OST) and video see-through (VST) systems, and provide perspectives on future developments in this rapidly evolving field.

This narrative review was conducted through a literature search of PubMed, Scopus, and Web of Science databases using the search terms “extended reality,” “virtual reality,” “augmented reality,” “mixed reality,” combined with “neurosurgery,” “pediatric,” “surgical navigation,” “medical education,” and “patient communication.” Articles published up to March 2026 in English were considered. Reference lists of identified articles were also reviewed to identify additional relevant studies. As this is a narrative review, a formal systematic search protocol with predefined inclusion/exclusion criteria was not employed, and the selection of studies was based on the authors’ judgment of relevance and quality.

## AI-BASED LESION SEGMENTATION FOR XR VISUALIZATION

Effective XR visualization in neurosurgery relies on accurate three-dimensional reconstruction of anatomical structures and pathological lesions. Manual segmentation is time-consuming, subject to inter-observer variability, and often impractical in clinical workflows. AI-based automatic segmentation has emerged as a solution, with deep learning methods achieving performance comparable to expert radiologists[25,27].

Among available frameworks, the nnU-Net architecture represents a significant advancement in medical image segmentation. This self-configuring method automatically adapts its architecture, preprocessing, and training procedures to each new dataset, achieving state-of-the-art results across diverse segmentation challenges including brain tumor segmentation on the BraTS challenge[25]. In a head-to-head comparison of nnU-Net and DeepMedic methods for autosegmentation of pediatric brain tumors, nnU-Net generally showed superior performance, particularly for tumor core and enhancing tumor regions, although both methods achieved reasonable accuracy[44].

Transformer-based architectures have also shown promise for brain tumor segmentation. The Swin UNETR model, combining Swin Transformers with a U-Net-like encoder-decoder structure, has demonstrated excellent performance on brain tumor segmentation tasks[21]. These models can process multimodal magnetic resonance imaging (MRI) sequences including T1-weighted, T1-contrast enhanced, T2-weighted, and fluid-attenuated inversion recovery images to generate comprehensive tumor segmentations that differentiate between tumor core, peritumoral edema, and enhancing regions.

Beyond tumor segmentation, AI has been applied to other pediatric neurosurgical pathologies. For craniosynostosis, convolutional neural network-based classification systems using multi-view cranial radiographs have demonstrated that EfficientNet-based models can accurately classify craniosynostosis subtypes and assess suture line patency from plain radiographs, potentially reducing the need for computed tomography (CT) imaging and associated radiation exposure in pediatric patients[29]. Similarly, a combined approach using deep learning with three-dimension stereophotogrammetry has been developed for craniosynostosis diagnosis[11]. Such diagnostic AI systems can be integrated with XR platforms to provide surgeons with AI-assisted preoperative assessments visualized in three-dimensional space.

The integration of AI segmentation with XR visualization follows a typical workflow : medical images are processed through trained neural networks to generate volumetric segmentations; these segmentations are converted to three-dimensional mesh models; and the models are imported into XR platforms for visualization and interaction. As illustrated in Fig. 1, this pipeline—from AI-based brain MRI segmentation to AR overlay on the surgical field—can now be largely automated, al-

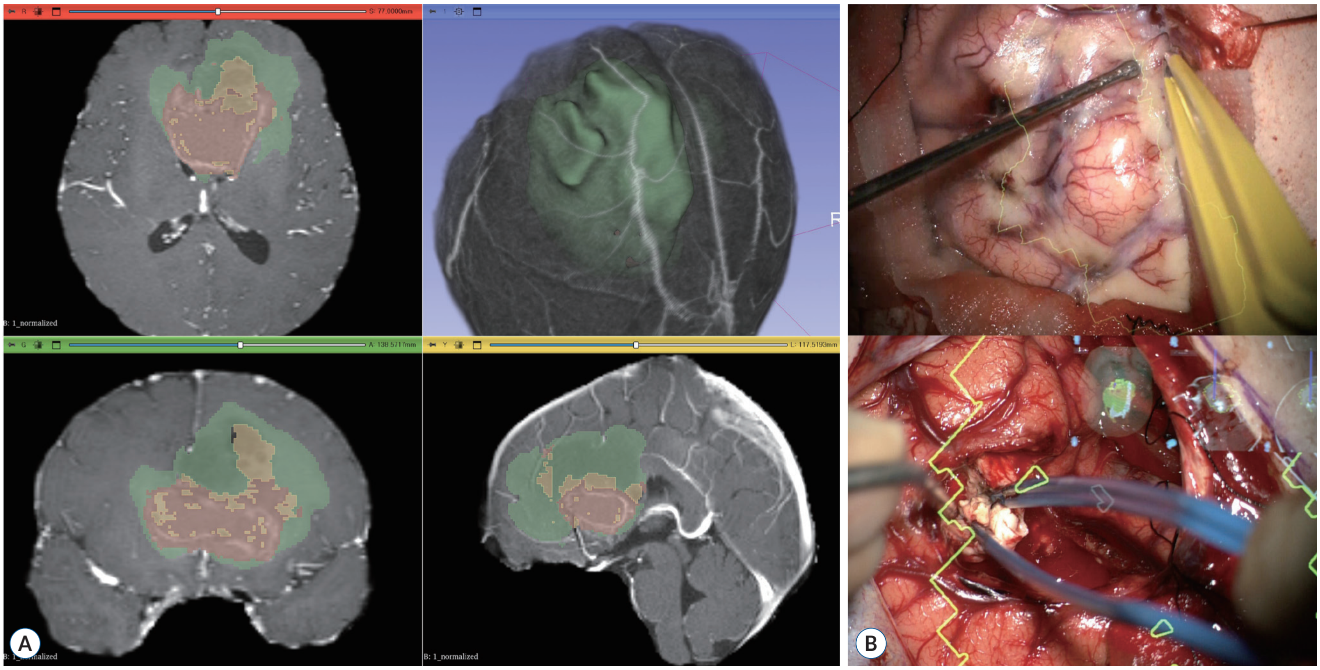

**Fig. 1.** Integration of artificial intelligence-based segmentation with extended reality visualization. A : AI-based brain MRI segmentation demonstrating automatic delineation of tumor core (red), peritumoral edema (green), and enhancing tumor (yellow) using deep learning algorithms. The segmentation results are converted to three-dimensional mesh models for XR visualization. B : Clinical application of AR navigation in neurosurgery. The surgeon's view shows overlay of segmented tumor boundaries and critical structures on the operative field, enabling real-time guidance during resection. AI : artificial intelligence, MRI : magnetic resonance imaging, XR : extended reality, AR : augmented reality.

lowing rapid generation of patient-specific XR visualizations from routine clinical imaging[15].

## XR-ASSISTED SURGICAL NAVIGATION

Surgical navigation has been a cornerstone of modern neurosurgery since its introduction in the 1980s. Conventional navigation systems require surgeons to divert their visual attention from the surgical field to monitor displays, creating a disconnect that can impair surgical efficiency and safety. XR-based navigation addresses this limitation by overlaying navigation data directly onto the surgeon's view of the operative field, potentially improving spatial awareness and reducing cognitive load[9,31]. Over the past decade, numerous AR navigation systems have been developed and validated for neurosurgical applications. Table 1 provides a comprehensive summary of the reported accuracy of these systems, ranging from projector-based and smartphone-based platforms to head-mounted displays (HMDs) and microscope-integrated solutions, with target registration errors varying from sub-millimeter to several millimeters depending on the registration method and clinical scenario.

### OST systems

OST HMDs use semitransparent optics to overlay computer-generated images onto the user's direct view of the real world. Table 2 compares the key technical characteristics of OST and VST display technologies relevant to neurosurgical applications, including differences in visual perception, latency, virtual occlusion capability, lighting adaptability, and safety features. Devices such as the Microsoft HoloLens represent the most widely studied OST platforms in neurosurgical applications[42]. The primary advantage of OST systems is the preservation of natural visual perception, maintaining depth cues and allowing direct visualization of the surgical field without video processing delays.

Recent first-in-human results using a standalone OST head-worn navigation system for intracranial drain placement demonstrated high accuracy with a 100% first-pass success rate, comparing favorably with conventional electromagnetic navigation[43]. The system allowed hands-free navigation with real-

**Table 1.** AR navigation accuracy in neurosurgery

| Study | N | AR system | Registration | TRE/accuracy | Application |
|---|---|---|---|---|---|
| Besharati Tabrizi et al.[2] (2015) | 10 head phantoms; 5 patients | Projector-based AR overlaying segmented tumors on head/brain surface | Point-based with 5 fiducial markers | Mean projection error 0.8±0.25 mm (phantom), 1.2±0.54 mm (patients) | Brain tumor localization and intraoperative visualization |
| Hou et al.[22] (2016) | 35 patients | iPhone-assisted AR lesion localization | Image-based alignment using CT/MRI and skin markers | 97.7% of markers within ≤5 mm; median offset vs. neuronavigation 2.9 mm (max 4.2 mm) for supratentorial lesions | Low-cost localization of intracranial lesions and surface projection |
| Watanabe et al.[45] (2016) | 6 patients; phantom tests | “Trans-Visible Navigator” tablet-based see-through AR | Optical tracking (VICON) with markers on phantom/patient | Phantom spatial resolution ≈1 mm | Volumetric neuronavigation for brain tumor resection, skin incision and craniotomy planning |
| Incekara et al.[24] (2018) | 25 patients | HoloLens mixed-reality planning tool | Image-to-patient alignment on patient’s head | Median difference vs. neuronavigation 0.4 cm (IQR, 0–0.8 cm) in tumor border localization | Preoperative/planning overlay of brain tumors on scalp |
| Carl et al.[6] (2019) | 47 patients | Microscope-based AR | iCT automatic | 0.83±0.44 mm | Transsphenoidal surgery |
| Gibby et al.[16] (2021) | 1 skull phantom with 3 deep targets; 5 users, 70 trajectories | VisAR on HoloLens 2 for needle guidance | Alignment of holographic fiducials to CT-visible AprilTags | Mean radial error 3.62±1.71 mm; angle error 2.30°±1.28° | Deep brain target acquisition /minimally invasive needle navigation |
| Pojskić et al.[37] (2022) | 39 patients | Microscope-based AR | iCT automatic | 0.82±0.37 mm | Skull base meningiomas |
| de Almeida et al.[10] (2022) | Scalp phantom; multiple conditions, 10 iterations per condition | Mobile (smartphone-based) AR neuronavigation | Variable number of registration points, image-based | Best-case mean target error 2.6±1.6 mm | Scalp surface point localization/ low-cost navigation substitute |
| Van Doormaal et al.[42] (2019) | 13 patients | HoloLens | Point-based fiducial | 4.4–7.2 mm FRE | Neuronavigation |
| Van Gestel et al.[43] (2025) | 10 patients | Standalone HMD | Surface-based registration | High accuracy; clinically acceptable drain position in all cases | Intracranial drain placement |
| Olexa et al.[35] (2025) | 20 patients | Headset-contained AR stereotactic neuronavigation | Markerless, surface-based registration (AR) compared to reference array CIN | AR registration accuracy 2.16±0.12 mm vs. baseline 0.73±0.29 mm; statistically equivalent within 2.5–3 mm margins | General cranial stereotactic navigation in routine neurosurgery |
| Ma et al.[34] (2025) | 75 patients | Spine AR navigation | Marker-based registration | Higher pedicle screw accuracy vs. conventional methods | Multicenter spinal instrumentation |
| Carbone et al.[4] (2025) | 6 patients | VOSTARS wearable OST AR | Infrared-tracked markers | Submillimetric-low-millimetric error vs. conventional navigation | Neurosurgical navigation phantom and clinical scenarios |
| Ruggiero et al.[40] (2025) | 10 patients | AR craniofacial guidance | Fiducials/markerless (mixed) | Millimetric osteotomy accuracy | Pediatric craniofacial surgery |
| Shawarba et al.[41] (2025) | 43 patients | Microscope-based AR | Multimodal image registration | Precise localization of epileptogenic zones; feasibility demonstrated | Focal pediatric epilepsy surgery |

AR : augmented reality, TRE : target registration error, CT : computed tomography, MRI : magnetic resonance imaging, IQR : interquartile range, iCT : intraoperative computed tomography, VisAR : Visual Augmented Reality (Novarad), FRE : fiducial registration error, HMD : head-mounted display, CIN : conventional image navigation, VOSTARS : Video Optical See-Through Augmented Reality Surgical System, OST : optical see-through

**Table 2.** Comparison of optical see-through and video see-through display technologies for neurosurgical applications

| Feature | Optical see-through | Video see-through |
|---|---|---|
| Visual perception | Direct view of reality; natural depth perception maintained | Camera-mediated view; depth perception may be altered |
| Latency | No latency for real-world view; virtual content may lag | System latency affects entire view; typically 20–50 ms |
| Virtual occlusion | Limited; virtual objects appear semitransparent | Full occlusion possible; realistic depth integration |
| Lighting conditions | Virtual content may be difficult to see in bright OR lighting | Display brightness independent of ambient light; consistent visualization |
| Safety | Retains direct vision if system fails | Complete vision loss if camera system fails |
| Image enhancement | Limited to virtual content overlay | Can apply filters, zoom, and enhancement to entire view |
| Example devices | Microsoft HoloLens, Magic Leap | Meta Quest Pro, Apple Vision Pro, Galaxy XR, VOSTARS |

OR : operating room, VOSTARS : Video Optical See-Through Augmented Reality Surgical System

time trajectory visualization, representing a significant advancement in practical AR navigation implementation. Separately, clinical evaluation of holographic navigation using point-based registration on AR glasses has reported fiducial registration errors of 4.4–7.2 mm, illustrating the range of accuracy achievable with current OST platforms[42].

However, OST systems have inherent limitations. The virtual content appears semitransparent and may be difficult to visualize under bright operating room lights. Field of view is typically limited compared to natural vision, and vergence-accommodation conflicts can cause visual fatigue during prolonged use. Additionally, accurate calibration is required to align virtual and real-world coordinate systems, with small errors potentially resulting in significant navigational inaccuracies[31].

## VST systems

VST systems capture the real world through cameras and display a composite image combining real and virtual content on opaque displays (Table 2). This approach offers several advantages : virtual objects can fully occlude real objects, enabling more realistic depth representation; display brightness and contrast can be controlled independently of ambient lighting; and image processing can be applied to the camera feed to enhance visualization.

A notable example of a hybrid approach is the VOSTARS (Video Optical See-Through Augmented Reality Surgical System) platform, which combines OST capabilities with video augmentation. Comparative evaluation against traditional infrared and electromagnetic navigation for neurosurgical applications has demonstrated competitive accuracy, achieving a mean application accuracy of 1.87 mm and supporting its potential for clinical neurosurgical navigation[4,5].

VST systems have limitations including potential latency between real-world events and display rendering. Complete reliance on camera systems means any camera malfunction would eliminate real-world visualization entirely.

## Registration methods

Accurate registration between virtual models and patient anatomy is essential for XR navigation. Traditional point-based registration using fiducial markers has been the standard approach, achieving registration errors typically in the range of 1–3 mm. However, this method requires time-consuming marker placement and is subject to errors from marker movement or imprecise localization[2].

Markerless registration techniques using surface scanning and AI-driven feature matching have emerged as promising alternatives. An automatic markerless registration approach based on the iterative closest point algorithm has been applied to facial plastic and reconstructive surgery, achieving registration accuracy of 1.49–1.95 mm suitable for clinical use without the need for fiducial markers[30]. This approach has significant implications for pediatric applications, where avoiding additional procedural steps is particularly valuable. Microscope-based AR with intraoperative CT integration has achieved even higher precision, with reported accuracy of 0.83 mm in transsphenoidal surgery[6].

## Clinical applications in pediatric neurosurgery

AR-guided navigation has shown particular promise in pediatric craniofacial surgery. Clinical experience with AR in craniosynostosis repair and cranioplasty procedures has demonstrated practical implementation, with the AR system allowing visualization of planned osteotomy lines and cranial vault reconstruction targets directly on the patient's anatomy[40].

In the context of focal pediatric epilepsy surgery, a retrospective feasibility study investigating AR-assisted microsurgical multimodal image-guided surgery demonstrated that AR integration enhanced visualization of epileptogenic zones and their relationship to eloquent cortex, supporting more precise surgical planning and execution in this challenging pediatric population[41].

For brain tumor resection, a comparative study of MR-guided glioblastoma resection versus standard neuronavigation showed that the MR system allowed intraoperative visualization of tumor boundaries and critical structures, with improved surgeon confidence in identifying tumor margins[20]. Although focused on adult patients, the principles are directly applicable to pediatric brain tumors. In spinal surgery, a randomized multicenter trial demonstrated that AR navigation significantly enhanced the accuracy of pedicle screw placement (98.0% vs. 91.7%; $p<0.05$)[34]. These intraoperative applications, as depicted in Fig. 2, illustrate how AR-guided navigation enables surgeons to maintain visual attention on the procedural field while accessing real-time trajectory and anatomical information through head-mounted or tablet-based displays.

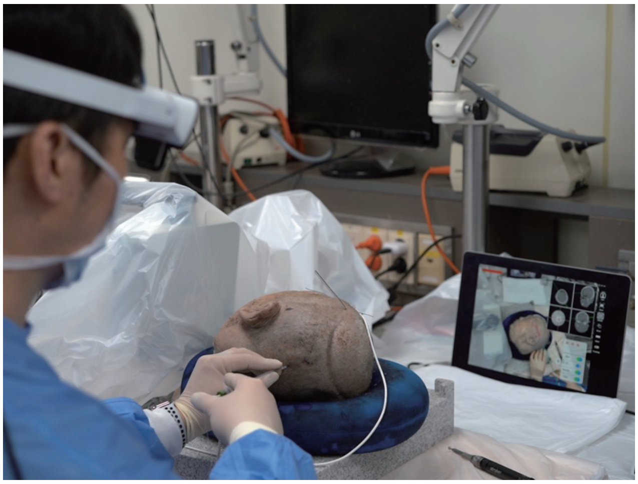

**Fig. 2.** AR-guided external ventricular drain placement. A demonstration on a cadaveric model shows a surgeon wearing smart glasses performing EVD insertion while a tablet display mounted in front shows the ventricular system and planned trajectory. The AR system visualizes the target ventricle and optimal insertion path, allowing the surgeon to maintain visual attention on the procedural field while accessing navigation information. AR : augmented reality, EVD : external ventricular drain.

## XR FOR NEUROSURGICAL EDUCATION AND TRAINING

Neurosurgical training traditionally relies on cadaveric dissection, observation of live surgeries, and progressive operative responsibility under supervision. However, access to cadaveric specimens is limited, ethical constraints restrict certain training scenarios, and the complexity of modern neurosurgery demands mastery of procedures that trainees may rarely encounter during residency. XR technologies offer innovative solutions to these educational challenges[8].

### Anatomical education

VR platforms enable immersive exploration of neuroanatomy in ways impossible with traditional methods. One such approach integrates photographic three-dimensional models of the real brain into VR for neurosurgical resident education, allowing virtual dissection of actual brain specimens with preservation of realistic tissue textures and colors[38]. Assessment of neurosurgical residents showed improved anatomical understanding and favorable subjective evaluation of the VR learning experience compared to conventional teaching methods.

Comprehensive three-dimensional anatomical atlases of the cerebrum, cerebellum, and brainstem have also been developed using XR simulations, enabling trainees to interactively explore brain structures in their spatial relationships, rotating and sectioning the virtual models to appreciate complex three-dimensional anatomy that is difficult to convey through two-dimensional images[17-19].

### Surgical simulation

VR surgical simulators have demonstrated effectiveness for procedural skill training. A randomized double-blind controlled trial evaluating immersive VR surgical simulator training for pedicle screw placement showed that the VR-trained group achieved significantly improved accuracy and reduced insertion time compared to conventionally trained controls, supporting the value of VR simulation for developing technical skills applicable to pediatric spinal procedures[49].

The NeuroTouch simulator, incorporating haptic feedback, has been used to establish proficiency benchmarks for brain tumor resection[1]. Practice on an AR/haptic simulator with a library of virtual brains has also been shown to improve residents' ability to perform ventriculostomy, further demonstrating the translational value of XR-based simulation training$^{50)}$.

### Preoperative planning and case-based learning

XR technologies facilitate case-based learning by allowing trainees to explore patient-specific anatomy before surgery. As shown in Fig. 3, modern XR platforms such as MedicalHolodeck integrate AR overlay on the surgical field, two-dimensional MRI viewing with three-dimensional volume rendering, and libraries of interactive VR educational modules, demonstrating their versatility for both intraoperative guidance and medical education. The "Canopy Approach," using immersive VR for bottom-up target-based preoperative planning in pediatric neurosurgery, exemplifies this application by enabling surgical teams to virtually position themselves at the planned operative corridor and visualize deep targets from the surgeon's perspective, improving understanding of surgical approach and anatomical relationships$^{32)}$.

Collaborative VR environments have also been explored for case-based teaching. A pilot study using immersive collaborative VR for case-based teaching in thoracic surgery demonstrated feasibility and favorable learner responses$^{14)}$. Similar approaches could enhance pediatric neurosurgical education by enabling remote multi-user discussion of complex cases in a shared virtual space.

## XR FOR PATIENT COMMUNICATION AND INFORMED CONSENT

Communicating complex neurosurgical procedures to patients and families is challenging, particularly in pediatric cases where caregivers must make decisions on behalf of their children. Traditional informed consent processes rely on verbal explanations, two-dimensional diagrams, and generic illustrations that may inadequately convey the specific nature of planned procedures. XR technologies offer innovative approaches to enhance patient understanding and consent quality. As conceptualized in Fig. 4, AR-assisted explanation allows clinicians to display three-dimensional models of the child's pathology—showing tumor location, planned surgical approach, and relationship to surrounding structures—in a format that families can intuitively grasp, in contrast to the challenges posed by

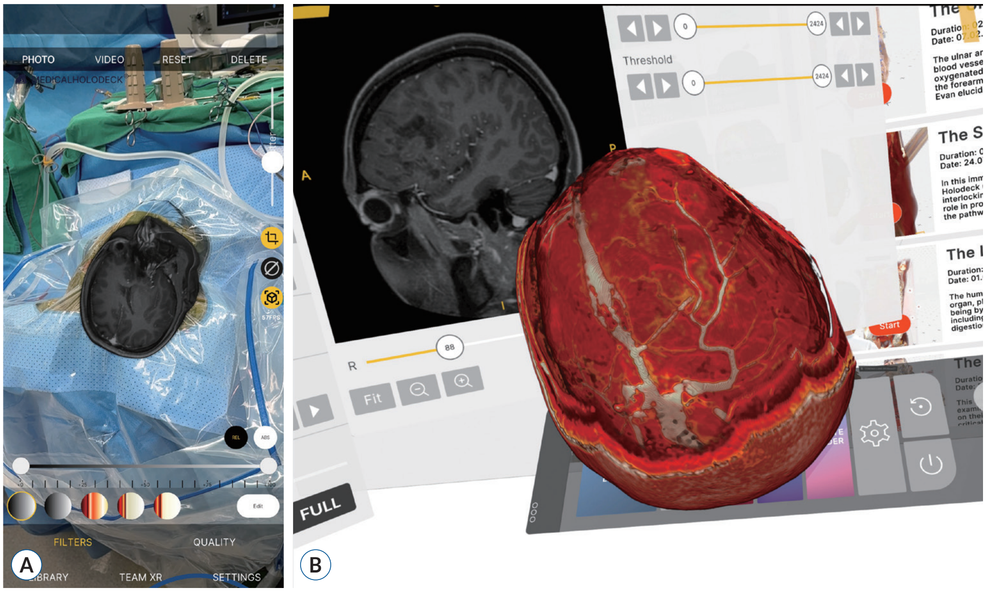

**Fig. 3.** Extended reality platforms for surgical planning and simulation. A : A mobile device running MedicalHolodeck software displays patient DICOM imaging data, allowing the surgeon to examine cross-sectional views and specific anatomical structures from the operative perspective. As registration accuracy improves, this approach may serve as a practical tool for preoperative planning of scalp incision design and patient positioning. B : A head-mounted display (HMD)-based VR platform (MedicalHolodeck) enables direct import of patient DICOM data for preoperative surgical simulation. Multiplanar reformatted views can be examined alongside three-dimensional volume-rendered models. Selective voxel masking allows sequential removal of superficial layers to reveal subsurface anatomy beneath the skin and skull, facilitating three-dimensional assessment of spatial relationships and simulation of tumor removal.

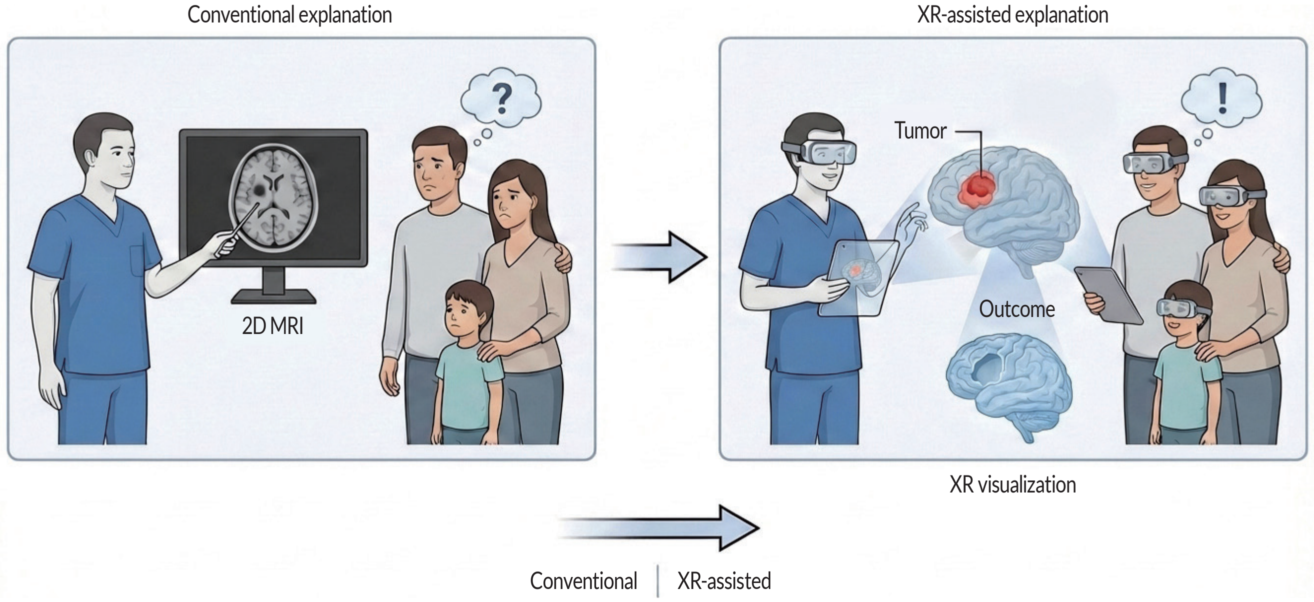

**Fig. 4.** Schematic illustration comparing conventional and XR-assisted patient communication for pediatric brain tumor surgery. The left panel demonstrates a conventional explanation utilizing a two-dimensional MRI display. The right panel illustrates the XR-assisted approach, where the clinician uses an XR device to present a three-dimensional model of the child's brain. This enables the patient and parents to clearly visualize the tumor location, planned surgical approach, and anticipated postoperative outcome, facilitating improved comprehension and informed consent. This image was generated and iteratively modified (via targeted region redrawing) using FigureLab.ai, powered by the Nano Banana Pro model. MRI : magnetic resonance imaging, XR : extended reality.

**Table 3.** Studies on XR-assisted patient and family communication in surgery

| Study | N | Technology | Specialty | Key outcomes |
|---|---|---|---|---|
| Eijlers et al.[12] (2019) | 17* | VR (meta-analysis) | Pediatric various | Anxiety SMD, -0.74 (*p*<0.001) |
| House et al.[23] (2020) | 17 patients | MR (HoloLens) | Epilepsy surgery | Better comprehension (*p*=0.001), reduced anxiety (*p*=0.008) |
| Perin et al.[36] (2021) | 33 patients | VR (Surgical Theater) | Brain tumor | Improved comprehension, no increased anxiety |
| Wright et al.[48] (2021) | 50 patients | VR (Surgical Theater) | Neurosurgery (brain tumor) | Improved understanding, satisfaction, and physician-patient alliance; high acceptance of VR as adjunct to consultation |
| Lo et al.[33] (2023) | 12 patients | AR leaflet | Pediatric cleft | Mental effort 2.0 vs. 4.75 (*p*=0.0003) |
| Wehrkamp et al.[46] (2025) | 4 neurosurgery studies within 16 total (1067 patients) | VR, AR, MR HMDs showing patient-specific anatomy/pathology | Multispecialty including neurosurgery | Across neurosurgical cohorts, XR-assisted consent improved understanding, satisfaction, and often reduced anxiety versus standard methods; evidence strongest for VR |

*Number of studies in meta-analysis. XR : extended reality, VR : virtual reality, SMD : standardized mean difference, MR : mixed reality, AR : augmented reality, HMD : head-mounted display

conventional two-dimensional imaging. Table 3 provides a summary of the current evidence for XR-assisted patient and family communication in surgical settings, encompassing studies on VR, AR, and MR modalities across multiple specialties including neurosurgery, epilepsy surgery, and pediatric craniofacial conditions, with endpoints ranging from comprehension scores and anxiety measures to patient satisfaction.

## Three-dimensional visualization for informed consent

A randomized clinical trial comparing informed consent using three-dimensional VR visualization versus standard explanation for brain tumor surgery demonstrated that patients in the VR group had significantly better understanding of their condition and planned procedure, with improved satisfaction regarding the consent process[36]. The three-dimensional visualization allowed patients to see their specific tumor location and surgical approach in a patient-specific model derived from their own imaging.

The value of patient-specific three-dimensional models for informed consent has also been established using physical 3D-printed cerebral aneurysm models. Patients who received explanations using such models showed significantly higher understanding scores (4.7 vs. 2.5 out of 5.0; $p<0.05$) compared to conventional verbal explanation[28]. While using physical models rather than XR, this study established the principle that patient-specific three-dimensional visualization improves understanding of complex vascular pathology. The same approach can be implemented using XR visualization, potentially with advantages including the ability to visualize internal structures and surgical approaches that physical models cannot easily convey.

### AR and MR for surgical explanation

AR and MR provide unique opportunities for patient education by overlaying surgical planning information onto images of the patient or generic anatomical models. Evaluation of MR using Microsoft HoloLens for patient education in epilepsy surgery demonstrated significantly better comprehension ($p=0.001$) and reduced anxiety ($p=0.008$) compared to standard explanation[23]. A systematic review of AR applications in surgical consent and patient education has further identified growing applications across surgical specialties[13].

Feasibility studies using VR for patient informed consent in skull base tumors and intracranial vascular pathologies have demonstrated patient acceptance of VR-assisted consent, with patients reporting improved understanding of their conditions[47]. In the pediatric setting, AR education leaflets significantly reduced the mental effort required for families of cleft lip/palate patients to understand their child's condition (2.0 vs. 4.75; $p=0.0003$), highlighting the potential of AR tools for conveying complex anatomical information in age-appropriate and family-friendly formats[33].

### Reducing preoperative anxiety

VR has shown promise for reducing preoperative anxiety in pediatric patients. A systematic review and meta-analysis of VR in pediatrics demonstrated significant effects on reducing anxiety (standardized mean difference, -0.74; $p<0.001$) across 17 studies[12]. While specific applications in pediatric neurosurgery require further study, the principles are applicable : immersive VR experiences can distract children before procedures, familiarize them with the surgical environment, and reduce uncertainty about upcoming operations.

A comprehensive review of multimedia tools for enhancing informed consent in pediatric spinal surgery has supported the use of visual and interactive tools to improve caregiver understanding and reduce anxiety associated with complex spinal procedures in children[39]. XR technologies represent the most immersive form of such multimedia tools and warrant further investigation in pediatric neurosurgical contexts.

## DISCUSSION AND FUTURE DIRECTIONS

XR technologies have progressed from experimental curiosities to practical clinical tools with demonstrated applications across the spectrum of pediatric neurosurgical practice. The integration of AI-based segmentation with XR visualization has created powerful platforms for surgical planning, while AR navigation systems have achieved accuracy levels supporting clinical implementation, as summarized in Table 1. Educational applications have shown measurable improvements in trainee knowledge and skills, and XR-enhanced patient communication has improved understanding and satisfaction with informed consent, as detailed in Table 3.

Several challenges must be addressed for widespread clinical adoption. Current XR hardware remains bulky with limited battery life for standalone devices. Integration into surgical workflows requires attention to ergonomics, sterility, and compatibility with operating room equipment. Regulatory pathways and reimbursement mechanisms remain unclear[31].

The evidence base for XR in neurosurgery, while growing, still consists primarily of small studies and case series. Larger randomized controlled trials comparing XR-assisted surgery to conventional approaches are needed to definitively establish clinical benefits. Standardized evaluation metrics for XR navigation accuracy and clinical outcomes would facilitate comparison across studies and systems. A systematic review of evaluation metrics for AR in neurosurgical applications identified significant heterogeneity in reported metrics, highlighting the need for methodological consensus[31].

In the Korean and East Asian context, the adoption of XR technologies in neurosurgery has been steadily growing. Korean neurosurgical groups have contributed studies on VR-based neuroanatomical education using photographic three-dimensional brain models and AI-based craniosynostosis classification using deep learning, demonstrating active engagement with XR-related technologies. However, regulatory considerations specific to the Korean healthcare environment must be addressed. The Ministry of Food and Drug Safety has yet to establish comprehensive guidelines specifically tailored to XR surgical navigation devices, and reimbursement pathways through the Health Insurance Review and Assessment Service remain undefined for XR-assisted procedures. The advanced digital infrastructure and high-speed connectivity available in Korean hospitals provide a favorable environment for XR deployment. In the broader East Asian context, institutions in Japan, China, and Taiwan have also reported clinical experiences with AR navigation and VR education platforms, suggesting regional momentum toward XR integration. Collaborative multicenter initiatives across East Asian institutions could accelerate clinical validation and regulatory harmonization for XR technologies in neurosurgery.

This narrative review has certain limitations inherent to its methodology. The absence of a systematic search protocol with predefined inclusion/exclusion criteria introduces potential selection bias. The literature was selected based on the authors' judgment, and relevant studies may have been inadvertently omitted. Furthermore, the rapidly evolving nature of XR technology means that new developments may emerge between the completion of this review and its publication.

Looking forward, several technological developments promise to enhance XR capabilities for pediatric neurosurgery. Advances in display technology will improve visual quality, field of view, and comfort. The development of surgical microscopes with integrated AR capabilities for brain tumors[6,37] will enable seamless integration of XR visualization into standard surgical workflows. Improved tracking systems using inside-out tracking and AI-based pose estimation will reduce setup time and improve registration accuracy.

The combination of XR with intraoperative imaging including ultrasound and intraoperative MRI will enable real-time updating of navigation data to account for brain shift. AI algorithms will increasingly automate registration, segmentation, and surgical guidance, reducing technical barriers to XR implementation.

## CONCLUSION

XR technologies have emerged as valuable tools for pediatric neurosurgery, with applications spanning surgical planning, intraoperative navigation, education, and patient communication. AI-based lesion segmentation provides the foundation for accurate three-dimensional visualization, while both OST and VST AR systems offer complementary advantages for surgical navigation. Educational applications have demonstrated improvements in anatomical knowledge and procedural skills, and XR-enhanced communication tools improve patient and family understanding of complex conditions. While challenges remain in hardware development, workflow integration, and evidence generation, the trajectory of XR technology development strongly supports continued investment in research and clinical implementation. As these technologies mature, they hold substantial promise for improving outcomes in pediatric neurosurgical care.

## AUTHORS' DECLARATION

### Conflicts of interest

No potential conflict of interest relevant to this article was reported.

### Informed consent

This type of study does not require informed consent.

### Author contributions

Conceptualization : THR, EHK; Data curation : THR, SC; Formal analysis : THR, JHM; Funding acquisition : THR; Methodology : THR, EHK, SGK; Project administration : EHK; Visualization : THR, SC; Writing - original draft : THR; Writing - review & editing : EHK, JHM, SGK, JHC

### Data sharing

None

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## References

1. AlZhrani G, Alotaibi F, Azarnoush H, Winkler-Schwartz A, Sabbagh A, Bajunaid K, et al. : Proficiency performance benchmarks for removal of simulated brain tumors using a virtual reality simulator neurotouch. **J Surg Educ 72 :** 685-696, 2015
2. Besharati Tabrizi L, Mahvash M : Augmented reality-guided neurosurgery: accuracy and intraoperative application of an image projection technique. **J Neurosurg 123 :** 206-211, 2015
3. Cannizzaro D, Zaed I, Safa A, Jelmoni AJM, Composto A, Bisoglio A, et al. : Augmented reality in neurosurgery, state of art and future projections. A systematic review. **Front Surg 9 :** 864792, 2022
4. Carbone M, Cattari N, Cutolo F, Autelitano M, Cigna E, Ferrari V, et al. : Neuronavigation accuracy of the VOSTARS wearable AR platform vs traditional infrared navigation in a comparative study. **Sci Rep 15 :** 28982, 2025
5. Carbone M, Montemurro N, Cattari N, Autelitano M, Cutolo F, Ferrari V, et al. : Targeting accuracy of neuronavigation: a comparative evaluation of an innovative wearable AR platform vs. traditional EM navigation. **Front Digit Health 6 :** 1500677, 2025
6. Carl B, Bopp M, Voellger B, Saß B, Nimsky C : Augmented reality in transsphenoidal surgery. **World Neurosurg 125 :** e873-e883, 2019
7. Chang YZ, Wu CT : Application of extended reality in pediatric neurosurgery: a comprehensive review. **Biomed J 48 :** 100822, 2025
8. Chawla S, Devi S, Calvachi P, Gormley WB, Rueda-Esteban R : Evaluation of simulation models in neurosurgical training according to face, content, and construct validity: a systematic review. **Acta Neurochir (Wien) 164 :** 947-966, 2022
9. Dadario NB, Quinoa T, Khatri D, Boockvar J, Langer D, D'Amico RS : Examining the benefits of extended reality in neurosurgery: a systematic review. **J Clin Neurosci 94 :** 41-53, 2021
10. de Almeida AGC, Fernandes de Oliveira Santos B, Oliveira JLM : A neuronavigation system using a mobile augmented reality solution. **World Neurosurg 167 :** e1261-e1267, 2022
11. de Jong G, Bijlsma E, Meulstee J, Wennen M, van Lindert E, Maal T, et al. : Combining deep learning with 3D stereophotogrammetry for craniosynostosis diagnosis. **Sci Rep 10 :** 15346, 2020
12. Eijlers R, Utens EMWJ, Staals LM, de Nijs PFA, Berghmans JM, Wijnen RMH, et al. : Systematic review and meta-analysis of virtual reality in pediatrics: effects on pain and anxiety. **Anesth Analg 129 :** 1344-1353, 2019
13. Evans T, Turna A, Stringfellow TD, Jones GG : Uses of augmented reality in surgical consent and patient education - a systematic review. **PLOS Digit Health 4 :** e0000777, 2025
14. Feodorovici P, Sommer N, Bergedieck P, Lingohr P, Kalff JC, Schmidt J, et al. : Immersive collaborative virtual reality for case-based graduate student teaching in thoracic surgery: a piloting study. **Surg Open Sci 22 :** 40-45, 2024
15. Fick T, van Doormaal JAM, Tosic L, van Zoest RJ, Meulstee JW, Hoving EW, et al. : Fully automatic brain tumor segmentation for 3D evaluation in augmented reality. **Neurosurg Focus 51 :** E14, 2021
16. Gibby W, Cvetko S, Gibby A, Gibby C, Sorensen K, Andrews EG, et al. : The application of augmented reality-based navigation for accurate target acquisition of deep brain sites: advances in neurosurgical guidance. **J Neurosurg 137 :** 489-495, 2021
17. Gurses ME, Gungor A, Gökalp E, Hanalioglu S, Karatas Okumus SY, Tatar I, et al. : Three-dimensional modeling and augmented and virtual reality simulations of the white matter anatomy of the cerebrum. **Oper Neurosurg 23 :** 355-366, 2022
18. Gurses ME, Gungor A, Rahmanov S, Gökalp E, Hanalioglu S, Berker M, et al. : Three-dimensional modeling and augmented reality and virtual reality simulation of fiber dissection of the cerebellum and brainstem. **Oper Neurosurg 23 :** 345-354, 2022
19. Gurses ME, Hanalioglu S, Mignucci-Jiménez G, Gökalp E, Gonzalez-Romo NI, Gungor A, et al. : Three-dimensional modeling and extended reality simulations of the cross-sectional anatomy of the cerebrum, cerebellum, and brainstem. **Oper Neurosurg 25 :** 3-10, 2023
20. Haemmerli J, Khatchatourov S, Chaboudez E, Roth L, Sandralegar A, Janssen I, et al. : Surgical and clinical impacts of mixed reality-guided glioblastoma resection versus standard neuronavigation: improving tumor surgery. **Front Oncol 15 :** 1551937, 2025
21. Hatamizadeh A, Nath V, Tang Y, Yang D, Roth HR, Xu D : Swin UNETR: Swin transformers for semantic segmentation of brain tumors in MRI images in Crimi A, Bakas S (eds) : **Brainlesion: Glioma, Multiple Sclerosis, Stroke and Traumatic Brain Injuries.** Cham : Springer, 2022, pp272-284
22. Hou Y, Ma L, Zhu R, Chen X, Zhang J : A low-cost iPhone-assisted augmented reality solution for the localization of intracranial lesions. **PLoS One 11 :** e0159185, 2016

23. House PM, Pelzl S, Furrer S, Lanz M, Simova O, Voges B, et al. : Use of the mixed reality tool "VSI Patient Education" for more comprehensible and imaginable patient educations before epilepsy surgery and stereotactic implantation of DBS or stereo-EEG electrodes. **Epilepsy Res 159 :** 106247, 2020
24. Incekara F, Smits M, Dirven C, Vincent A : Clinical feasibility of a wearable mixed-reality device in neurosurgery. **World Neurosurg 118 :** e422-e427, 2018
25. Isensee F, Jaeger PF, Kohl SAA, Petersen J, Maier-Hein KH : nnU-Net: a self-configuring method for deep learning-based biomedical image segmentation. **Nat Methods 18 :** 203-211, 2021
26. Jean WC : Virtual and augmented reality in neurosurgery: the evolution of its application and study designs. **World Neurosurg 161 :** 459-464, 2022
27. Karschnia P, Young JS, Dono A, Häni L, Sciortino T, Bruno F, et al. : Prognostic validation of a new classification system for extent of resection in glioblastoma: a report of the RANO resect group. **Neuro Oncol 25 :** 940-954, 2023
28. Kim PS, Choi CH, Han IH, Lee JH, Choi HJ, Lee JI : Obtaining informed consent using patient specific 3D printing cerebral aneurysm model. **J Korean Neurosurg Soc 62 :** 398-404, 2019
29. Kim SM, Yang JS, Han JW, Koo HI, Roh TH, Yoon SH : Convolutional neural network-based classification of craniosynostosis and suture lines from multiview cranial X-rays. **Sci Rep 14 :** 26729, 2024
30. Kim YC, Park CU, Lee SJ, Jeong WS, Na SW, Choi JW : Application of augmented reality using automatic markerless registration for facial plastic and reconstructive surgery. **J Craniomaxillofac Surg 52 :** 246-251, 2024
31. Kos TM, Colombo E, Bartels LW, Robe PA, van Doormaal TPC : Evaluation metrics for augmented reality in neurosurgical preoperative planning, surgical navigation, and surgical treatment guidance: a systematic review. **Oper Neurosurg 26 :** 491-501, 2023
32. Lai GY, Phelps RRL, Singhal NS, Sullivan JE, Numis AL, Auguste KI : The "canopy approach": case series using immersive virtual reality for bottom-up target-based preoperative planning in pediatric neurosurgery. **Neurosurg Pract 4 :** e00038, 2023
33. Lo SJ, Chapman P, Young D, Drake D, Devlin M, Russell C : The cleft lip education with augmented reality (CLEAR) VR phase 2 trial: a pilot randomized crossover trial of a novel patient information leaflet. **Cleft Palate Craniofac J 60 :** 179-188, 2023
34. Ma Y, Wu J, Dong Y, Tang H, Ma X : Augmented reality navigation system enhances the accuracy of spinal surgery pedicle screw placement: a randomized, multicenter, parallel-controlled clinical trial. **Orthop Surg 17 :** 631-643, 2025
35. Olexa J, Chen C, Rastogi P, Sansur C, Rakovec M, Saadon JR, et al. : Clinical validation of a rapid, markerless, headset-contained augmented reality stereotactic neuronavigation system. **J Neurosurg 144 :** 472-478, 2025
36. Perin A, Galbiati TF, Ayadi R, Gambatesa E, Orena EF, Riker NI, et al. : Informed consent through 3D virtual reality: a randomized clinical trial. **Acta Neurochir (Wien) 163 :** 301-308, 2021
37. Pojskić M, Bopp MHA, Saß B, Carl B, Nimsky C : Microscope-based augmented reality with intraoperative computed tomography-based navigation for resection of skull base meningiomas in consecutive series of 39 patients. **Cancers (Basel) 14 :** 2302, 2022
38. Roh TH, Oh JW, Jang CK, Choi S, Kim EH, Hong CK, et al. : Virtual dissection of the real brain: integration of photographic 3D models into virtual reality and its effect on neurosurgical resident education. **Neurosurg Focus 51 :** E16, 2021
39. Rosa Filezio M, Sharma N, Thull-Freedman J, Ferri-de-Barros F, Santana MJ : Enhancing informed consent through multimedia tools in pediatric spinal surgery: a comprehensive review. **Front Pediatr 12 :** 1357462, 2024
40. Ruggiero F, Cercenelli L, Tarsitano A, Emiliani N, Stradiotti S, Babini M, et al. : Augmented reality in pediatric craniofacial surgery: clinical experience. **J Neurosurg Pediatr 36 :** 657-663, 2025
41. Shawarba J, Tomschik M, Wais J, Winter F, Dorfer C, Mayer F, et al. : Augmented reality (AR) in microsurgical multimodal image guided focal pediatric epilepsy surgery: results of a retrospective feasibility study. **Brain Spine 5 :** 104180, 2025
42. van Doormaal TPC, van Doormaal JAM, Mensink T : Clinical accuracy of holographic navigation using point-based registration on augmented-reality glasses. **Oper Neurosurg 17 :** 588-593, 2019
43. Van Gestel F, Frantz T, Buyck F, Gallagher AG, Geens W, Neuville Q, et al. : High-accuracy augmented reality guidance for intracranial drain placement using a standalone head-worn navigation system: first-in-human results. **Neurosurgery 96 :** 1217-1226, 2025
44. Vossough A, Khalili N, Familiar AM, Gandhi D, Viswanathan K, Tu W, et al. : Training and comparison of nnU-Net and DeepMedic methods for Autosegmentation of pediatric brain tumors. **AJNR Am J Neuroradiol 45 :** 1081-1089, 2024
45. Watanabe E, Satoh M, Konno T, Hirai M, Yamaguchi T : The trans-visible navigator: a see-through neuronavigation system using augmented reality. **World Neurosurg 87 :** 399-405, 2016
46. Wehrkamp K, Miksch RC, Polzer H, Gilbert F, Bühner M, Holzapfel BM, et al. : The impact of virtual-, augmented- and mixed reality during preoperative informed consent: a systematic review of the literature. **J Med Syst 49 :** 89, 2025
47. Westarp E, Saemann A, Zelechovski M, Faludi B, Cattin P, Soleman J, et al. : Virtual reality for patient informed consent in skull base tumors and intracranial vascular pathologies: a pilot study. **Acta Neurochir (Wien) 166 :** 455, 2024
48. Wright JM, Raghavan A, Wright CH, Shammassian B, Duan Y, Sajatovic M, et al. : Back to the future: surgical rehearsal platform technology as a means to improve surgeon-patient alliance, patient satisfaction, and resident experience. **J Neurosurg 135 :** 384-391, 2021
49. Xin B, Chen G, Wang Y, Bai G, Gao X, Chu J, et al. : The efficacy of immersive virtual reality surgical simulator training for pedicle screw placement: a randomized double-blind controlled trial. **World Neurosurg 124 :** e324-e330, 2019
50. Yudkowsky R, Luciano C, Banerjee P, Schwartz A, Alaraj A, Lemole GM Jr, et al. : Practice on an augmented reality/haptic simulator and library of virtual brains improves residents' ability to perform a ventriculostomy. **Simul Healthc 8 :** 25-31, 2013