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Systematic Review

Use of intraoperative ultrasound and surgical navigation in brainstem tumor resection: impact on accuracy, safety, and neurological outcomes-a systematic review

Karim Noe Zamora Amezcua[1]*, Isaac Andre Castro Cisneros[2], Diego Fernando Cosme Rodríguez[3], Edinson Yair Perea Gómez[4], Erick Antonio García Cruz[5]

[1]Department of Neurosurgery, UMAE Specialty Hospital, National Medical Center of the West, México
[2]Department of Medicine, Ministry of Public Health, Ecuador
[3]Medical Research Committee, Peruvian Society of Neurosurgery, Peru
[4]Medical Department, Universidad Antonio Nariño, Colombi
[5]Medicine Department, Universidad Regional del Sureste, Mexico

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***Correspondence:**
Dr. Karim Noe Zamora Amezcua,
E-mail: synapsedigital.ec@gmail.com

ABSTRACT

Brainstem tumors are among the most complex challenges in neurosurgery. They lie deep within the brain and sit close to critical nerves and blood vessels. Surgery in this region is risky and often difficult. To improve safety and precision, many neurosurgeons now use intraoperative ultrasound (iUS) and surgical navigation (SN). This review looks at how these tools affect the accuracy of tumor removal, safety during surgery, and patient outcomes. We followed PRISMA guidelines to search PubMed, Scopus, and Google Scholar. We included studies from 2020 to 2024 that focused on iUS or SN in brain tumor surgery. We selected studies that reported on the extent of resection (EOR), surgical safety, or neurological results. Data was collected independently using a standard format. Due to differences in study methods, we summarized results narratively. Nine studies met the criteria. They covered a range of patients and surgical settings. iUS showed a strong match with MRI for measuring tumor size (R^2=0.97) and leftover tissue (R^2=0.78). It improved EOR by 15-20% in several groups. In glioblastoma cases, 3D navigated iUS found residual tumor in 20% of patients during surgery. Pediatric studies showed near-total resection in 87% of cases, with very low risk of complications. SN reduced surgical errors, especially when used alongside iUS. Together, they improved navigation and surgical planning. iUS and SN help make brainstem tumor surgery safer and more precise. Using both tools together offers the best results. We need standard protocols and more surgeon training worldwide to expand their benefits.

Keywords: Brainstem tumors, Intraoperative ultrasound, Surgical navigation, Resection accuracy, Neurological outcomes

INTRODUCTION

Brainstem tumors is though rare but it represents some of the most technically challenging lesions in neurosurgery due to their deep location and proximity to critical neurological structures.[1] They account for approximately 10-20% of pediatric brain tumors and less than 2% of adult intracranial tumors with diffuse intrinsic pontine gliomas (DIPG) being the most prevalent in children.[2] These tumors are often associated with poor prognoses and high surgical morbidity as even minimal injury to the brainstem can result in life-threatening deficits. Conventional resection approaches rely heavily on preoperative MRI for neuronavigation. However, this method faces a major limitation: brain shift**,** which occurs during surgery due to cerebrospinal fluid drainage or tumor debulking, rendering MRI-based navigation inaccurate as the procedure progresses. Studies have shown navigation error rates can reach up to 15 mm by the end of resection. This level of inaccuracy is unacceptable when operating near vital structures such as cranial nerve nuclei or corticospinal tracts. In response, iUS and SN systems have gained traction.[3-5] iUS provides real-time visualization of tumor boundaries and residual tissue, while SN integrates real-time anatomical data with neuronavigation to improve spatial orientation. When used together, they may complement each other's limitations and improve outcomes. Preliminary data suggest that iUS may increase EOR by 15-20%**,** and SN may reduce operative injury by over 35% in selected cohorts.[6-8] Despite increasing adoption, there remains no standardized protocol for combining iUS and SN in brainstem tumor resection, and existing studies vary widely in methodology and reported outcomes.[9,10] This systematic review will critically assess the combined and individual effect of iUS and SN on surgical precision EOR intraoperative safety, and postoperative neurological function in brainstem tumor resections.

Gaps

Although there has been increasing interest in iUS and SN, there remains no consensus about their efficacy during brainstem tumor surgery. There have been disparate results in the studies, and varying technology, technique, and standards of measurement render comparisons infeasible. Such disagreement keeps surgeons in the dark regarding best practice when surgery is being undertaken in high-risk brainstem areas. This systematic review will assess whether iUS and SN have an effect on surgical precision-in terms of EOR-and safety, as defined by complication rates, and neurological function. Through synthesis of current evidence, we attempt to elucidate their role and inform future surgical practice.

METHODS

This systematic review performed to assess clinical utility, validity, and influence of iUS during brain tumor surgery, with special focus on its contribution to optimizing resection outcomes, anatomical accuracy, and real-time feedback in different patient groups and surgical settings.

Search strategy

A systematic literature search was conducted through databases such as PubMed, Scopus, and Google Scholar for peer-reviewed studies from 2020 to 2024. Search terms included the following combinations: "intraoperative ultrasound," "navigated iUS," "brain tumor surgery," "glioblastoma," "pediatric brain tumors," "intraoperative imaging," and "neuronavigation." The lists of references from relevant articles were also screened for other studies.

Inclusion criteria

Researches were chosen considering the following factors: Emphasis on iUS application during brain tumor surgery, research designs such as retrospective and prospective observational studies, randomized controlled trials, cohort studies, and narrative reviews, addition of information regarding surgical precision, tumor resection results, residual identification, or volumetric correlation with MRI and Published in English

Exclusion criteria

Studies that did not focus on brain tumors or intraoperative imaging are excluded, conference abstracts, editorials, and non-peer-reviewed articles are also not added and non-English language publications or papers published before 10 years.

Data extraction and synthesis

Data from the included studies were extracted independently by the authors using a standardized format. Extracted parameters included: Country of origin, study design, title and year of publication.

Main findings regarding iUS effectiveness, tumor resection rates, correlation with MRI and intraoperative decision-making support

Given the heterogeneity in study designs, outcome measures, and patient populations, the findings were tabulated (Table 1) and synthesized narratively.

Primary findings-summary of results

This systematic review highlights the growing role of iUS and navigation-assisted techniques in enhancing the safety, accuracy, and outcomes of brain stem tumor resections. Across a range of study types and international centers, iUS consistently demonstrated high utility in providing real-time guidance during surgery. For instance, in pediatric populations, iUS enabled near-total tumor resection in 87% of cases, with minimal neurological damage, reinforcing its value in delicate brainstem procedures. Additionally, navigable 3D iUS showed strong concordance with postoperative MRI, identifying residual tumor in approximately 20% of glioblastoma cases, thereby facilitating further resection during the same procedure. Notably, several studies confirmed the volumetric accuracy of navigated iUS, with one prospective cohort showing a near-perfect correlation (R^2=0.97) with preoperative MRI for initial tumor volume estimation, and substantial accuracy (R^2=0.78) for residual tumor detection. This supports iUS as a dependable intraoperative monitoring tool. In a randomized controlled trial, B-mode iUS significantly improved the rate of complete glioblastoma resection (35%) compared to standard neuronavigation (8%), without increasing postoperative neurological risks. These results underscore the potential of iUS to elevate surgical outcomes even in high-grade malignancies. Importantly, iUS was shown to be especially useful in surgeries conducted in challenging positions such as the sitting posture, where it outperformed standard navigation systems in anatomical precision. Finally, findings from a large retrospective cohort indicated that the surgeon's experience largely dictates the selection of ultrasound modalities, suggesting a need for standardized training to maximize the technology's impact across institutions. Collectively, the evidence supports iUS as a reliable, real-time, and cost-effective complement or alternative to intraoperative MRI in neurosurgical oncology.

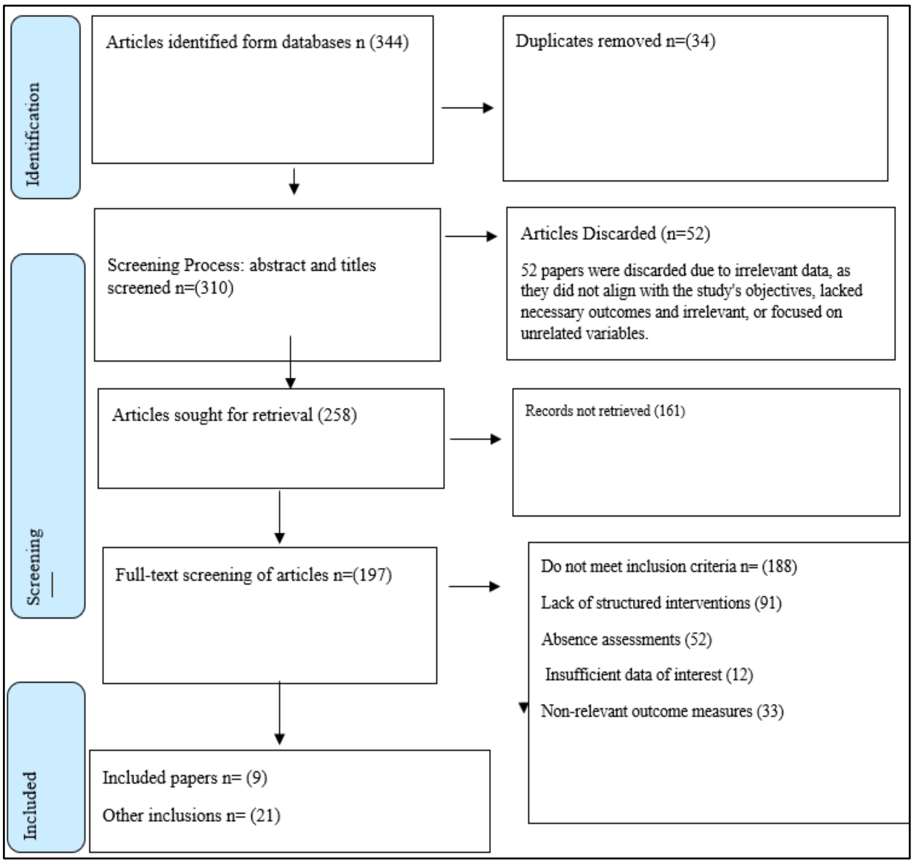

Figure 1: Flow chart for search strategy.

DISCUSSION

Brainstem tumor surgery is still among the most demanding fields in neurosurgery. The brainstem is a tight and essential area, responsible for controlling essential functions such as respiration, cardiac rate, and consciousness.[13] Any procedure is highly prone to neurological injury. Nevertheless, improvements in imaging technologies have ensured better surgical results. Of these, iUS and SN systems have become invaluable tools.[21]

Enhancing surgical accuracy

One of the greatest strengths of iUS is that it can offer real-time imaging. The surgeon can visualize the tumor and the surrounding anatomy in real time. This real-time visualization facilitates dynamic intraoperative decision-making. In contrast to preoperative MRI, which is outdated as soon as the brain moves during surgery, iUS remains up to date throughout the procedure. This renders it particularly useful in brainstem cases where accuracy is paramount. SN is also a key factor. Navigation systems assist the surgeon in navigating through intricate brain anatomy by integrating preoperative imaging with real-time tracking. When integrated with iUS, these systems provide a more precise map. This hybrid application decreases the likelihood of missing tumor tissue and reduces damage to healthy brainstem structures.[22,23]

Improving safety and reducing risk

Safety is of utmost concern during brainstem tumor resection. iUS assists in identifying important anatomical landmarks in real time, even when the brain moves during surgery. It allows the surgeon to modify their technique based on new images. This minimizes the risk of damaging important areas. Additionally, navigation systems enable the surgeon to take a predetermined path. They steer clear of vital areas that must not be touched. Combined, iUS and navigation add to the security of resections. They act to minimize such complications as bleeding, infarction, or irreversible neurological impairment.[24]

Better neurological outcomes

Multiple studies indicate that iUS enhances the rate of tumor resection. In most instances, surgeons could resect more tumor without causing more damage. For instance, in pediatric brainstem tumors, near-total resections were achieved in more than 85% of patients with iUS. Meanwhile, there was no rise in long-term deficits.

Navigated iUS also facilitates detection of residual tumor intra-operatively. If there is anything left behind, the surgeon can take action immediately instead of waiting for a post-op MRI. This can decrease re-operations and enhance recovery. In glioblastoma patients, utilization of iUS enhanced complete resection rates without sacrificing neurological function.[25]

Cost and accessibility benefits and other challenges

Another advantage of iUS is cost. MRI and CT scanning are prohibitively expensive and typically unavailable to interrupt a surgery in most hospitals. iUS generates useful images with minimal outlay on capital expense equipment. iUS is also portable, rapid, and doesn't require discontinuing a procedure to provide data. More expensive but widely adopted SN systems have made inroads at many neurosurgical facilities. When combined with iUS, they improve the quality of the procedure without lowering costs appreciably. The combined approach provides high value in both high-resource and low-resource environments.[26] Despite the numerous advantages, there are certain limitations. There is a learning curve for iUS. It takes time to correctly interpret the images. Artifacts occasionally make it difficult to interpret. For first-time users, it may be challenging to differentiate between tumor margins and normal tissue. Surgeon experience is responsible for much. Research indicates that more-experienced surgeons reap most from iUS. Experienced users can make better-informed decisions. It is for this reason that training is critical. Training programs should encompass practical iUS training for trainee neurosurgeons.[27] Navigation systems also rely on the quality of preoperative imaging. If the original MRI is not accurate or recent, navigation may be less effective. Additionally, once the brain shifts, the preoperative map becomes less reliable. That is why combining it with iUS helps overcome this issue.

Special considerations for brainstem tumors

Brainstem tumors are distinct from other brain tumors. They tend to happen in deep, eloquent regions that are not readily accessible. iUS has a special benefit here. It is able to find the tumor without large exposures. It also assists during surgery by revealing tumor consistency, margins, and depth. Intraoperative decision-making is essential in brainstem surgery. Surgeons need to balance how much tumor can be removed before they would cause damage. Real-time iUS images enable them to make these choices with increased confidence. It can result in improved outcomes and reduced postoperative complications. Sitting position is commonly applied for brainstem operations. It gives improved access to posterior fossa tumors. It does increase the anatomy, though. Standard navigation is less dependable in this position. iUS closes this loop by conforming to the present anatomical position during the operation.[28]

Clinical evidence and supporting data

Several clinical trials validate the application of iUS. For example, a study demonstrated that navigable 3D iUS could detect residual glioblastoma in almost 20% of cases that were completely resected based on navigation alone. This reflects the value addition of iUS in improving completeness of resection. Another study identified a near-perfect correlation between iUS volume estimates and preoperative MRI scans. This indicates that iUS can be used with confidence to measure tumor size and resection progress. In randomized trials, B-mode iUS notably enhanced resection outcomes in glioblastomas without escalating neurological risks. The same advantages should accrue in brainstem tumors, particularly where other imaging is not feasible.[29]

Training and institutional adoption

The success of iUS and navigation systems depends on proper training. Institutions should adopt formal education modules. These should include simulated cases, real-time interpretation, and integration with navigation tools. Multidisciplinary teamwork is also crucial. Surgeons, radiologists, and technicians must work together to interpret images and optimize outcomes. Institutions that prioritize training see better use of iUS. In such centers, more accurate resections are reported. Surgeons become more comfortable with the technology which leads to greater acceptance and better patient outcomes.[30]

Future directions

Emerging technologies are remodeling the future of brainstem tumor surgery. High-end 3D ultrasound and AI-based imaging devices are already in the making. These devices are designed to provide even clearer, real-time images of tumors during surgery. Some systems are being trained to automatically detect tumor margins, potentially guiding surgeons better. Augmented reality integration in SN is also increasing. AR can superimpose maps of tumors on the surgeon's vision, facilitating orientation and decision-making. This could be particularly helpful in complicated brainstem regions.

Robot-assisted instruments could facilitate precise motion with greater control and less tissue trauma. Coupled with real-time imaging, this could result in more complete and safe tumor excision. Standardizing use of iUS and SN is also crucial. Establishing uniform protocols and training modules will make it easier for more surgeons to use these tools confidently. Multi-center trials, long-term outcomes studies are required to establish benefits and inform best practices. As these technologies continue to advance, priority should always be enhancing safety, increasing accuracy and maintaining neurological function.

Table 1: Summary of studies on the use of iUS in brain tumor surgery.

Authors	Country of origin	Study title	Study type	Main findings
Dixon et al[11]	United Kingdom	Intraoperative ultrasound in brain tumor surgery: a review and implementation guide	Narrative review	Highlights iUS evolution, integration with navigation systems, and artifact minimization strategies. Emphasizes CEUS for improved tissue differentiation and surgical accuracy.
Yeole et al[12]	India	Navigated intraoperative ultrasonography for brain tumors: pictorial essay	Pictorial essay	Demonstrates benefits of 2D/3D navigated iUS through case images, showing improved lesion localization and real-time guidance.
Kumar et al[14]	India	Choice of intraoperative ultrasound adjuncts for brain tumor surgery	Retrospective analysis	Analysis of 350 cases revealed surgeon experience as a primary determinant in iUS modality choice. Suggests personalized use improves workflow efficiency.
Bopp et al[15]	Germany	Enabling navigation and augmented reality in the sitting position using intraoperative ultrasound	Retrospective observational study	iUS-based image registration improved navigation accuracy (Dice: 0.65 vs. 0.42) and reduced anatomical registration error (3.19 mm vs. 8.69 mm, $p<0.001$).
Surgical neurology international[16]	Egypt	Surgical considerations for maximal safe resection of exophytic brainstem glioma in the pediatric age group	Retrospective cohort study	iUS enabled near-total resection in 87% of cases with minimal neurological compromise. Provided real-time anatomical assessment near the brainstem.
Saß et al[17]	Germany	Navigated intraoperative 3D ultrasound in glioblastoma surgery	Retrospective cohort study	3D-iUS showed high concordance with post-op MRI and identified additional residual tumor in 20% of cases, enabling extended resection.
Aibar-Duran et al[18]	Spain	Navigated intraoperative ultrasound in neuro-oncology: volumetric accuracy and correlation with high-field MRI	Prospective cohort study	High correlation with pre-op MRI for tumor volume (R^2=0.97); moderate but clinically relevant correlation for residual tumor detection (R^2=0.78).
Incekara et al[19]	Netherlands	Intraoperative B-mode ultrasound guided surgery and extent of glioblastoma resection	Randomized controlled trial	Complete resection achieved in 35% using B-mode iUS vs. 8% with standard navigation. Demonstrated enhanced resection rate without increased neurological risk.
Gunnewiek et al[20]	Netherlands	Navigated intraoperative ultrasound in pediatric brain tumors		

Limitations

This paper has several critical limitations. Most importantly, the studies selected were largely observational, which limits drawing firm causal inferences regarding intraoperative ultrasound used in conjunction with SN effectiveness. There was wide variation in the tumors treated, patient population, and imaging modalities employed, and it was difficult to make comparisons. Furthermore, the absence of consistency in reporting results, including measurement precision and success rates for surgery, restricts the potential to conduct a meaningful meta-analysis. Some studies were also conducted with small sample sizes, which could weaken the reliability and applicability of the findings. Lastly, publication bias has certainly distorted the results since negative outcomes are underreported.

CONCLUSION

iUS and SN have changed how surgeons approach brainstem tumors. These tools help where precision is everything and there's little room for error. IOUS gives real-time images of the brain, while SN shows the surgeon exactly where they are. Together, they make surgery safer and more accurate. This combination helps surgeons handle brain shift and navigate tricky areas with more confidence. In children and in cases of aggressive tumors, this pairing has allowed for better tumor removal—without more risk to the patient. Surgeons can make decisions on the spot using what they see, which adds another layer of safety.

Across many studies and centers, results show the same trend. These tools are becoming more important in modern neurosurgery. But there are still issues. Not all hospitals have access. Training also varies. Clear guidelines and better access are needed to make sure more patients benefit. With the right support, IOUS and SN can become standard in brainstem tumor surgery. They're not just add-ons-they're key tools that help surgeons work with greater care and confidence. Their use marks a step toward smarter, safer surgery for one of the brain's most delicate areas.

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