NEUROSONOLOGY X NEUROSURGERY

Intraoperative ultrasound use in cranial neurosurgery- The basics and initial experience

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Abstract

Reliable spatial orientation in neurosurgery is of utmost importance. Anatomical landmarks-based orientation or sulcal identification is insufficiently accurate for the requirements of modern times neurosurgery

Intraoperative ultrasound (IoUS) is affordable and widely available, easy to use, does not require additional equipment nor installation, and does not use additional any expendable material. It is mainly used (but not limited) to localize, optimize approach and evaluate resection of expansions of all origins, but also in vascular neurosurgery, hydrocephalus and malformations.

The paper reviews the possibilities of intraoperative ultrasound use in cranial neurosurgery, and also introduces the basic aspects of intraoperative use.

The significance of IoUS in contemporary neurosurgery is improving with the technical development and advances within the field. The basic role in localization of the lesions is still not used to the extent it deserves, or should be used, while there are already numerous other possibilities providing exceptionally reliable intraoperative information regarding all aspects of surgical substrates and treatment.

Keywords: intraoperative ultrasound; neurosurgery; cranial

DOI: https://doi.org/10.55005/sjns.v1i1.4

Introduction

Reliable spatial orientation in neurosurgery is of utmost importance. Anatomical landmark-based orientation or sulcal identification is insufficiently accurate for the requirements of modern neurosurgery [1]. Neuronavigation has been designated as one of the most important breakthroughs in surgery, and it is certain that high-profile neurosurgery cannot be performed without one such system. On the other hand, there are numerous system flaws, particularly with orientation in real time intraoperatively, when all structures change and/or move relative to the pre-programmed state of the neuronavigation [2].

Intraoperative use of magnetic resonance imaging (MRI) and computed tomography (CT) allows neurosurgeons to overcome these limitations by complementing the initial findings with subsequent intraoperative assessment uploaded into the navigation system, increasing the reliability of the system [3]. However, intraoperative diagnostics have a number of limitations, most of which are financial but also encompass spatial orientation and overall examination complexity [4]. Above all, intraoperative MRI and CT devices are extremely expensive, which is a problem in less developed centers and low- and middle-income countries. Moreover, even though intraoperative imaging increases the safety and improves surgical treatment in general, it is not recognized by the recommendations and guidelines of regulatory bodies [5]. Therefore, it is impossible to charge for this additional intraoperative tool, perhaps representing the primary issue in high-income countries and commercially oriented centers, which can afford these systems [6,7].

In contrast, intraoperative ultrasound (IoUS) is affordable and widely available, easy to use, does not require additional equipment or installation, and does not use any additional expendable material. It is mainly used to localize lesions, optimize the operative approach, and evaluate the extent of resection but not limited to these purposes [1]. Although IoUS was initially introduced into neurosurgery in 1978 by Reid [8], this technology has largely been unexplored due to its limitations in terms of bone interference, poor image quality (of that times systems) and lack of familiarity among neurosurgeons [9].

Most of these limitations have now been overcome. This article article emphasizes the important role IoUS may have in neurosurgery. Despite its steep learning curve, IoUS may facilitate neurosurgery.

Ultrasound basics and practical adjustments for intraoperative use

The basic principles of general ultrasound examination and neuroultrasonography apply to its intraoperative use.

Beginner users should expect to see images similar to those obtained from T2 MRI sequence, albeit somewhat between the native and contrast-enhanced series, or contrast-enhanced CT. IoUS exceeds the quality of native CT images, but it does not replace CT and should not be used to intraoperatively complement insufficient native CT findings.

Transducer selection

Prior to IoUS use, an adequate transducer should be selected based on the desired features.

1. Frequency: High frequency allows improved image resolution. Low frequency allows improved penetration.
    a. 3 MHz: good penetration, but poor resolution; capable of penetrating a thin temporal bone or skull in children
    b. 7 MHz: acceptable balance between resolution and penetration; most used in neurosurgery
    c. 10–12 MHz: better resolution at the cost of penetration; used for the superficial lesions
2. The size of the transducer: Larger transducers often provide better image quality but are difficult to access. There are four general types of intraoperative probes for use in neurosurgery:
    a. craniotomy (approximately 30x10 mm)
    b. burr-hole (approximately 10x10 mm)
    c. "hockey stick" with flexible tip (approximately 30x10 mm)
    d. minimally invasive (approximately 6-7 mm radius)

Although dedicated probes exist, the exam may often be performed using the usual probes which are widely available. The frequent lack of access to dedicated probes should not be considered a limitation to regular use. Linear probes penetrate more superficially and may be more suitable for beginner use, although they might require craniotomy enlargement due to their larger size.

Navigated ultrasound is a powerful tool that combines the benefits of real-time ultrasound imaging with the ability to track the probe, facilitating image-guided navigation (10, 11).

Approach to the patient

Fully immersive dedicated probes for intraoperative use may be sterilized and used within the watery environment without the use of gel. When using regular or older generation intraoperative transducers, the probe requires gel and should be placed into watertight sterile protection foil to prevent gel spill into the operating field. There should be enough gel between the probe and the sterile foil to enable proper functioning of the IoUS.

After preparing the probe in sterile fashion, the operating field should be prepared, and there should be no air between the probe and the tissue (1).

- The operating table should be maneuvered to position the patient's head and craniotomy transducer at the highest point, allowing for saline filling, reducing artifacts, and expanding the field visualized by the probe.
- The control panel should be covered with sterile foil to facilitate manipulation.
- The craniotomy should be large enough to enable visualization of the entire lesion.
    e. A slightly larger craniotomy allows for better visualization, while the dural opening can be adjusted according to the transdural IoUS findings.
    f. The dual craniotomy technique is an alternative to a larger craniotomy and includes an additional mini craniotomy sufficient in size to accommodate the transducer that is separate from the main craniotomy.
    g. For an ultrasound-guided biopsy, a craniotomy should be large enough for both the transducer and a biopsy needle.
- Initial ultrasonography is performed in the standard planes until the target structure is visualized. Then, the probe moves according to the neurosurgeon's need to visualize the structure from different angles.
- If available, the transducer should be registered with intraoperative neuronavigation. This co-registration may be combined with preoperative imaging (12).

Device Settings

Depending on the IoUS system used, there are several features which may be used to further enhance the acquired images:

- *Tissue Harmonic Intensity*: This option, which improves picture quality, should be active if available.
- *Image gain* and *brightness* are set at the beginning of the ultrasonography and may be corrected during the exam.
- The exam begins without field enlargement. The depth should be set according to the preoperative images for optimal anatomical orientation and resolution. Once the structure is localized, magnification is adjusted if needed.
- *Color Doppler* and *PowerDoppler* may be used to evaluate vascularization.

Ultrasonic display features

Normal structures of the brain and surrounding structures are seen as:

1. Hyperechoic: falx, tentorium, choroid plexus, and pineal gland.
2. Isoechoic: normal brain tissue.
3. Hypoechoic: brainstem
4. Anechoic (no signal): ventricular system and basal cisterns, CSF, and liquid.

Pathological structures:

1. Hyperechoic lesions: blood, solid intracranial tumors, vascular lesions (arteriovenous malformations, cavernomas, hemangiomas, and so on), capsules of cystic lesions, calcifications, high-grade gliomas, metastases
2. Moderate hyperechoic lesions: low-grade brain tumors, some metastases
3. Hypoechoic or anechoic lesions: cysts, chronic and subacute hematomas, necrotic zones of glioblastomas, abscesses

Foreign bodies (metal, glass, plastic, bone fragments) are usually hyperechoic. However, as most ultrasound signals are reflected from the surface of these objects rather than spread through them, only a probe-oriented surface can be visualized. The quality of the images may change substantially due to artifacts.

Mair et al. proposed stratifying neoplastic lesions into one of four grades (grades 0–3) on the basis of their ultrasonic echogenicity and border visibility.

- Grade 3: clearly identifiable with a clear border with normal tissue
- Grade 2: clearly identifiable but without clear border with normal tissue
- Grade 1: difficult to identify and without clear border with normal tissue
- Grade 0: lesions that could not be identified

High-grade gliomas, cerebral metastases, meningiomas, ependymomas, and haemangioblastomas demonstrated a median ultrasonic visibility grade 2 or greater, while low-grade astrocytomas and oligodendrogliomas demonstrated a median ultrasonic visibility grade 2 or less. (13)

Intraoperative ultrasound in cranial surgery

IoUS is commonly used in neurosurgery for the following surgeries:

- Tumors: localization, biopsy, resection, identification of feeders or drainage blood vessels in vascular tumors, as well as for assessment of the preciosity of venous sinuses)
- Infection: localization, identification, and aspiration driven by ultrasound, as well as completeness of evacuation
- Vascular lesions: localization and identification of lesions, identification of feeders and drainage blood vessels, transience of blood vessels postoperatively
- Hydrocephalus: catheter placement
- *Arnold-Chiari* malformation: decompression assessment

Lesion localization and optimal approach planning

Ultrasound examination can provide information about the location, size of lesions, as well as the interposition or proximity of blood vessels or ventricles. Small subcortical lesions are easily identified and clearly demarcated from the surrounding parenchyma (14) (***Figure 1***).

Recently, these features were used in patients with intracerebral hematoma to complement endoscopy for minimally invasive treatment. (15)

Resection Control

During brain tumor resection, IoUS provides a quick and accurate real-time assessment and allows for optimal safe resection and confirmation of the completeness of resection of solid lesions (10).

IoUS fusion with MRI through the neuronavigation system is particularly useful for intraoperative orientation and evaluation of tumor resection and is the best method for correction of errors from neuronavigation (***Figure 2***).

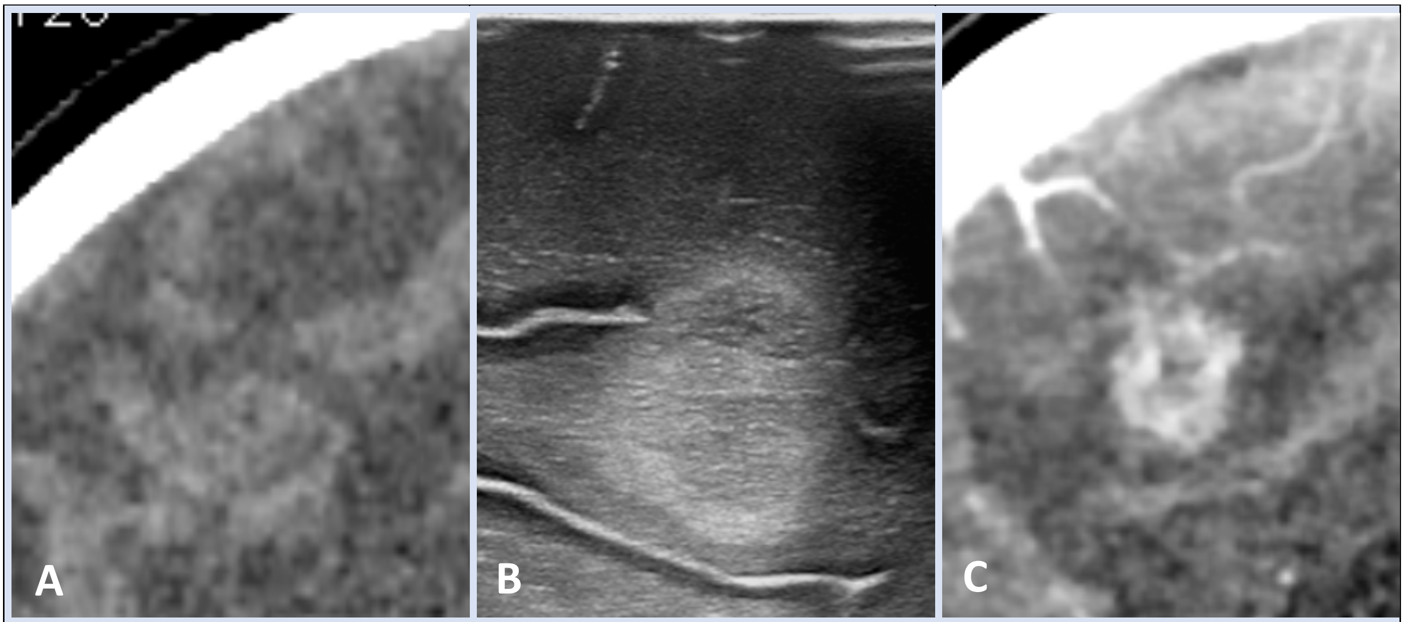

Figure 1. Comparative view of a frontal region metastasis.
A. CT without contrast enhancement; B. IoUS; C. CT with contrast enhancement.

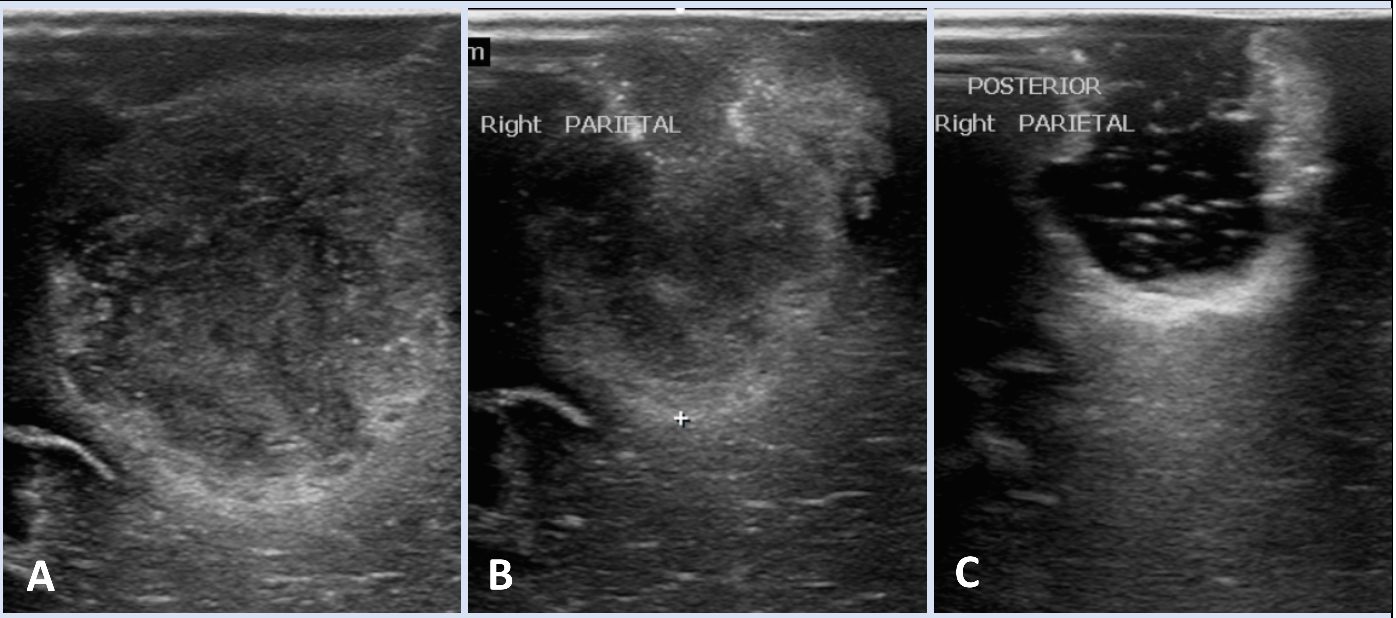

Figure 2. Intraoperative images obtained at different stages of brain tumor surgery shown in identical planes. A) before resection; B) during resection with the remainder of the tumor; C) after a complete resection.

In high-grade gliomas, contrast-enhanced IoUS in addition to 5-aminolevulinic acid guided resection allows for additional refinement and the greatest possible extent of resection (16, 17).

Vascularization and tumor features

Doppler sonography evaluation in tumor surgery allows for evaluation of the general vascularization of the lesion, localization of major arterial feeders and veins, and determination of venous sinuses patency or obliteration of the sinuses (18).

IoUS elastosonography has also elucidated key features of intracranial meningiomas, including meningioma consistency and the brain-meningioma interface, especially for hard-consistency meningiomas and those presenting with an adherent slip-brain interface (19).

Vascular neurosurgery

Micro Doppler provides information about blood flow and is useful in arteriovenous malformation and aneurysm surgeries because it enables real-time visualization of blood vessels and flow (20). This technology can also verify disruption of flow after aneurysm occlusion and identify an aneurysm inside a hematoma (21)

Early postoperative complications

After dural closure and just before repositioning of the bone flap, the final IoUS scan allows for the identification of early intracerebral hemorrhage or hydrocephalus formation (1).

Biopsy

The previously mentioned artifact feature may be used to visualize a needle in real time when performing a biopsy, and adding small dents to the top of the biopsy needle creates a visible and recognizable artifact (1). IoUS is therefore used to accurately locate a needle in the tissue when taking samples for a biopsy with results comparable to a stereotaxic biopsy while allowing additional monitoring of perioperative complications (22).

A biopsy can be performed in deep structures because real-time visualization allows for identification of the target structure and biopsy needle, while facilitating avoidance of deep anatomical structures such as the choroid plexus or large blood vessels. A three-dimensional ultrasound has proven to be the most adequate for this technique (1, 23). This technology also allows for monitoring of perioperative complications (22).

Catheter placement in hydrocephalus

The use of IoUS for the placement of permanent cerebrospinal fluid shunt catheters is associated with a decreased risk of shunt revision and may apply to temporary catheters as well (24). A burr-hole probe should be used through the same burr hole as the cather, although different burr-holes for the probe and catheter may also be drilled (25, 26).

In a study by Crowley et al., the use of IoUS was associated with a statistically significant decrease in shunt revisions, such that 21.7% of shunts required revision when the IoUS was used compared with 29.3% when IoUS was not used. The benefit of US was found to be more profound for occipital shunts (26). Recently, a study comparing the results with the use of IoUS and stereotactic navigation was started (27).

In children, neonatal acoustic windows allow quick assessment of the existence of intracranial lesions. The acoustic window has long been used in the evaluation of hydrocephalus or ventricular catheter position both intra- and postoperatively (28).

Evaluation of decompression in surgery *Arnold-Chiari* malformations

In patients with Arnold-Chiari type I malformation, decompressive surgery can be performed under IoUS surveillance, which allows assessment of ventral and dorsal decompression. Although morphological assessment is possible, evaluation of CSF flow is not, and the real impact of decompressive surgery may not be examined (29).

Education and Training

In addition to official courses endorsed by the professional societies and led by a few pioneer groups, it is important to mention that self-training options are available as well. Currently, two initiatives exist.

USim - developed by Camelot Biomedical Systems, Genova, Italy, and the Besta NeuroSim Center, Milan, Italy, as a dedicated app that transforms any smartphone into a "virtual ultrasound probe." This may simulate the application of iUS neurosurgery through a series of anonymized, patient-specific cases of different central nervous system tumors for education, simulation, and rehearsal purposes (30).

Customized Low-Cost Model for Hands-on Training - developed by the group from Tata Memorial Hospital, Mumbai, India, as an agar-based, low-cost customizable model using commonly available echogenic objects as targets. This allows the clinician to perform various training tasks like depth ultrasonography, target localization, and biopsy and resection cavity ultrasonography (31). In addition, a recent Frontiers in Oncology Research Topic on "Intraoperative Ultrasound in Brain Tumor Surgery: State-Of-The-Art and Future Perspectives" may provide further useful references (32).

Conclusion

The importance of IoUS in contemporary neurosurgery has yet to become fully recognized. Its basic functionality in localizing lesions lesions is often unmobilized, and there there are already numerous other technologies that provide reliable intraoperative information regarding all aspects of surgical substrates and operative approaches.

However, we emphasize the ease of use and likely conceptual familiarity of IoUS for neurosurgeons. We encourage all neurosurgeons to use this technique when appropriate, particularly young neurosurgeons who may come to appreciate IoUS as an essential tool in their neurosurgical armamentarium.

We hope that this manuscript will raise awareness of IoUS and its features and promote its usage among neurosurgeons in clinical practice.

Disclosures

Conflict of Interest: The author certify that he have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the institutional ethical standards and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from the reported individuals.

Funding: No funding was received for this research.

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References

1. Ivanov M, Wilkins S, Poeata I, Brodbelt A. Intraoperative ultrasound in neurosurgery - a practical guide. Br J Neurosurg. 2010;24(5):510-7. doi: 10.3109/02688697.2010.495165.
2. Gerard IJ, Kersten-Oertel M, Petrecca K, Sirhan D, Hall JA, Collins DL. Brain shift in neuronavigation of brain tumors: A review. Med Image Anal. 2017;35:403-20. doi: 10.1016/j.media.2016.08.007.
3. Senft C, Bink A, Franz K, Vatter H, Gasser T, Seifert V. Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial. Lancet Oncol. 2011;12(11):997-1003. doi: 10.1016/s1470-2045(11)70196-6.
4. Nimsky C. Intraoperative MRI in glioma surgery: proof of benefit? Lancet Oncol. 2011;12(11):982-3. doi: 10.1016/s1470-2045(11)70219-4.
5. Gerganov VM, Samii A, Giordano M, Samii M, Fahlbusch R. Two-dimensional high-end ultrasound imaging compared to intraoperative MRI during resection of low-grade gliomas. J Clin Neurosci. 2011;18(5):669-73. doi: 10.1016/j.jocn.2010.08.017.
6. Hall WA, Kowalik K, Liu H, Truwit CL, Kucharezyk J. Costs and benefits of intraoperative MR-guided brain tumor resection. Acta Neurochir Suppl. 2003;85:137-42. doi: 10.1007/978-3-7091-6043-5_19.
7. Abraham P, Sarkar R, Brandel MG, Wali AR, Rennert RC, Lopez Ramos C, et al. Cost-effectiveness of Intraoperative MRI for Treatment of High-Grade Gliomas. Radiology. 2019;291(3):689-97. doi: 10.1148/radiol.2019182095.
8. Reid MH. Ultrasonic visualization of a cervical cord cystic astrocytoma. AJR Am J Roentgenol. 1978;131(5):907-8. doi: 10.2214/ajr.131.5.907.
9. Šteňo A, Buvala J, Babková V, Kiss A, Toma D, Lysak A. Current Limitations of Intraoperative Ultrasound in Brain Tumor Surgery. Frontiers in Oncology. 2021;11(851). doi: 10.3389/fonc.2021.659048.
10. Moiyadi AV, Shetty P. Direct navigated 3D ultrasound for resection of brain tumors: a useful tool for intraoperative image guidance. Neurosurg Focus. 2016;40(3):E5. doi: 10.3171/2015.12.FOCUS15529.
11. Shetty P, Yeole U, Singh V, Moiyadi A. Navigated ultrasound-based image guidance during resection of gliomas: practical utility in intraoperative decision-making and outcomes. Neurosurgical Focus FOC. 2021;50(1):E14. doi: 10.3171/2020.10.Focus20550.
12. Bastos DCDA, Juvekar P, Tie Y, Jowkar N, Pieper S, Wells WM, et al. Challenges and Opportunities of Intraoperative 3D Ultrasound With Neuronavigation in Relation to Intraoperative MRI. Frontiers in Oncology. 2021;11(1463). doi: 10.3389/fonc.2021.656519.
13. Mair R, Heald J, Poeata I, Ivanov M. A practical grading system of ultrasonographic visibility for intracerebral lesions. Acta Neurochirurgica. 2013;155(12):2293-8. doi: 10.1007/s00701-013-1868-9.
14. Smith H, Taplin A, Syed S, Adamo MA. Correlation between intraoperative ultrasound and postoperative MRI in pediatric tumor surgery. J Neurosurg Pediatr. 2016;18(5):578-84. doi: 10.3171/2016.5.PEDS15739.

15. Sadahiro H, Nomura S, Goto H, Sugimoto K, Inamura A, Fujiyama Y, et al. Real-time ultrasound-guided endoscopic surgery for putaminal hemorrhage. J Neurosurg. 2015;123(5):1151-5. doi: 10.3171/2014.11.Jns141508.
16. Della Pepa GM, Ius T, La Rocca G, Gaudino S, Isola M, Pignotti F, et al. 5-Aminolevulinic Acid and Contrast-Enhanced Ultrasound: The Combination of the Two Techniques to Optimize the Extent of Resection in Glioblastoma Surgery. Neurosurgery. 2020;86(6):E529-E40. doi: 10.1093/neuros/nyaa037.
17. Ye D, Yu T, Shi J, Piao H. Comparison of intraoperative magnetic resonance imaging, ultrasound, 5-aminolevulinic acid, and neuronavigation for guidance in glioma resection: A network meta-analysis. Glioma. 2020;3(1):3-12. doi: 10.4103/glioma.glioma_5_20.
18. Della Pappa GM, Marchese E, Pedicelli A, Olivi A, Ricciardi L, Rapisarda A, et al. Contrast-Enhanced Ultrasonography and Color Doppler: Guided Intraoperative Embolization of Intracranial Highly Vascularized Tumors. World Neurosurg. 2019;128:547-55. doi: 10.1016/j.wneu.2019.05.142.
19. Della Pepa GM, Menna G, Stifano V, Pezzullo AM, Auricchio AM, Rapisarda A, et al. Predicting meningioma consistency and brain-meningioma interface with intraoperative strain ultrasound elastography: a novel application to guide surgical strategy. Neurosurgical Focus FOC. 2021;50(1):E15. doi: 10.3171/2020.10.Focus20797.
20. Stendel R, Pietilä T, Al Hassan AA, Schilling A, Brock M. Intraoperative microvascular Doppler ultrasonography in cerebral aneurysm surgery. J Neurol Neurosurg Psychiatry. 2000;68(1):29-35. doi: 10.1136/jnnp.68.1.29.
21. Siasios I, Kapsalaki EZ, Fountas KN. The role of intraoperative micro-Doppler ultrasound in verifying proper clip placement in intracranial aneurysm surgery. Neuroradiology. 2012;54(10):1109-18. doi: 10.1007/s00234-012-1023-y.
22. Satyarthee GD, Chandra PS, Sharma BS, Mehta VS. Comparison of Stereotactic and Ultrasound-guided Biopsy of Solid Supratentorial Tumor: A Preliminary Report. Asian J Neurosurg. 2017;12(4):664-9. doi: 10.4103/1793-5482.215765.
23. Berger MS. Ultrasound-guided stereotaxic biopsy using a new apparatus. Journal of Neurosurgery. 1986;65(4):550-4. doi: 10.3171/jns.1986.65.4.0550.
24. Wilson TJ, Stetler WR, Al-Holou WN, Sullivan SE. Comparison of the accuracy of ventricular catheter placement using freehand placement, ultrasonic guidance, and stereotactic neuronavigation: Clinical article. Journal of Neurosurgery JNS. 2013;119(1):66-70. doi: 10.3171/2012.11.Jns111384.
25. Ajmera S, Motiwala M, Khan NR, Smith LJ, Giles K, Vaughn B, et al. Image Guidance for Ventricular Shunt Surgery: An Analysis of Hospital Charges. Neurosurgery. 2019;85(4):E765-E70. doi: 10.1093/neuros/nyz090.
26. Crowley RW, Dumont AS, Asthagiri AR, Torner JC, Medel R, Jane JA, Jr., et al. Intraoperative ultrasound guidance for the placement of permanent ventricular cerebrospinal fluid shunt catheters: a single-center historical cohort study. World Neurosurg. 2014;81(2):397-403. doi: 10.1016/j.wneu.2013.01.039.
27. Leu S, Halbeisen F, Mariani L, Soleman J. Intraoperative ultrasound-guided compared to stereotactic navigated ventriculoperitoneal shunt placement: study protocol for a randomised controlled study. Trials. 2021;22(1):350. doi: 10.1186/s13063-021-05306-5.
28. Machado HR, Machado JC, Contrera JD, Assirati JA, Jr., Martelli N, Colli BO. Ultrasonographic evaluation of infantile hydrocephalus before and after shunting. A study in 20 children. Childs Nerv Syst. 1985;1(6):341-5. doi: 10.1007/bf00270820.
29. McGirt MJ, Attenello FJ, Datoo G, Gathinji M, Atiba A, Weingart JD, et al. Intraoperative ultrasonography as a guide to patient selection for duraplasty after suboccipital decompression in children with Chiari malformation Type I. J Neurosurg Pediatr. 2008;2(1):52-7. doi: 10.3171/PED/2008/2/7/052.
30. Perin A, Prada FU, Moraldo M, Schiappacasse A, Galbiati TF, Gambatesa E, et al. USim: A New Device and App for Case-Specific, Intraoperative Ultrasound Simulation and Rehearsal in Neurosurgery. A Preliminary Study. Oper Neurosurg (Hagerstown). 2018;14(5):572-8. doi: 10.1093/ons/opx144.
31. Singh V, Shaikh S, Shetty P, Moiyadi A. Customized Low-Cost Model for Hands-on Training in Intraoperative Ultrasound for Neurosurgeons: Our Experience and Review of Literature. World Neurosurgery. 2020;143:564-71.e2. doi: 10.1016/j.wneu.2020.07.044.
32. Del Bene M, DiMeco F, Unsgård G. Editorial: Intraoperative Ultrasound in Brain Tumor Surgery: State-Of-The-Art and Future Perspectives. Frontiers in Oncology. 2021;11. doi: 10.3389/fonc.2021.780517._