

# Intraoperative Ultrasound with Saline-Filled Silicone Applicators: An Innovative Echogenic Marker for Real-Time Neuronavigation

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**Abstract** Intraoperative ultrasound (ioUS) is a valuable real-time navigation tool in neurosurgery, yet its precision can be limited by the absence of stable echogenic landmarks. This study presents an innovative technique employing medical-grade silicone applicators or balloons filled with 0.9% saline solution as echogenic markers to enhance intraoperative orientation and navigation. Ten clinical cases involving supratentorial, brainstem, and spinal lesions were analyzed. The proposed markers demonstrated high echogenic contrast, stable visibility, and biocompatibility, enabling precise localization of lesions, safe definition of surgical trajectories, and verification of resection completeness. Compared with traditional cottonoid markers, saline-filled silicone applicators exhibited superior stability, adaptability to various anatomical conditions, and minimal tissue trauma. Their integration into ioUS workflows provided a cost-effective, easily reproducible, and dynamic alternative to neuronavigation and intraoperative MRI. The technique enhances surgical safety, minimizes injury to eloquent structures, and improves the radicality of tumor resections, making it a practical addition to modern neurosurgical armamentarium.

**Keywords** Intraoperative ultrasound, Echogenic marker, Neuronavigation, Saline-filled silicone applicator, Brain tumor surgery, Real-time imaging, Neurosurgery, Intraoperative navigation, Brain shift compensation, Minimally invasive surgery

## 1. Introduction

The technology of intraoperative ultrasonography (IOUS) was first presented by Kikuchi and colleagues (Japan) at the Second International Congress on Acoustics held in Cambridge, Massachusetts, USA, in 1956 [25]. Subsequent research confirmed its diagnostic value in localizing intraparenchymal pathological foci [5,8,42]. In 1978, Reid reported the first use of two-dimensional B-mode for intraoperative ultrasound mapping [36].

Despite these publications, after the introduction of ultrasound into neurosurgical practice in the 1950s, the method did not gain widespread adoption and was not integrated into daily clinical routine. This was due to both the technological limitations of early ultrasound systems and the rapid development of alternative neuroimaging techniques. Specifically, the widespread introduction of computed tomography (CT) in the 1970s, followed by magnetic resonance imaging (MRI) in the 1980s, significantly diminished interest in the ultrasound method. However, despite the obvious advantages of CT and MRI, these technologies did not provide truly intraoperative, real-time navigation, which limited their applicability in dynamically changing intraoperative conditions.

The efficacy of intraoperative ultrasonography (IOUS) has been confirmed in a wide range of clinical scenarios, including the localization of subcortical and deep-seated lesions, revision and replacement of ventriculoperitoneal shunts in patients with hydrocephalus, performance of stereotactic biopsies for deep-seated lesions, and diagnosis of intraventricular hemorrhages in newborns [4,7,9,11,16, 26,43,45]. The use of IOUS allows for the reconstruction of spatial relationships between a pathological focus and anatomical landmarks, facilitating the selection of an optimal surgical approach, minimization of damage to healthy tissue, and, consequently, improvement of functional outcomes.

However, even with the use of modern preoperative imaging modalities, such as 3 Tesla magnetic resonance imaging (MRI) with slice thicknesses of up to 1 mm, precise intraoperative localization of deep-seated or intraparenchymal lesions without a cortical representation remains a challenging task. An error of even a few millimeters can lead to unintentional resection of functionally significant areas, increasing the risk of postoperative complications and mortality.

To address this problem, various materials capable of serving as echogenic markers for IOUS and providing real-time anatomical orientation have been proposed in the literature [14,46]. Despite the shared concept, none of these approaches gained widespread acceptance or were supported by systematic studies.

In the present work, we propose a modified technique based on the use of medical silicone applicators or balloons filled with 0.9% NaCl solution (saline) as echogenic markers. Unlike the cottonoid patties used previously, such devices possess stable acoustic properties, reproducible echogenicity, and biocompatibility. An additional advantage is the ability to adjust the balloon's volume and shape, allowing adaptation to the specific features of the surgical cavity and reducing the risk of mechanical impact on brain tissue.

This technique, integrated into clinical practice since the early 2000s, has proven its practical value and has been described in a number of publications [13,23,24,40,41]. Its application provides clearer visualization of intraoperative anatomy, assists the surgeon in determining the optimal surgical approach, enables precise trajectory planning towards the pathological focus, and increases the extent of resection while simultaneously reducing the risk of damage to functional structures.

## 2. Materials and Methods

This study presents a modified technique based on the use of saline-filled silicone applicators as echogenic landmarks for intraoperative ultrasonography. The technique was illustrated by a series of clinical cases performed by a single surgeon. Ten patients who underwent surgical treatment using this technique starting from 2006 were retrospectively selected (Table 1): five patients with subcortical lesions, two patients operated on using an anterior transcallosal approach, and three patients with pathology of the brainstem and spinal cord.

Intraoperative ultrasonography was performed using the Aloka Prosound  $\alpha$ 10 system (Hitachi Aloka Medical, Ltd., Tokyo, Japan) with three types of transducers: UST-536 ("hockey stick," linear, 4.44–13.33 MHz), UST-9120 (neonatal convex, 5.0–10.0 MHz), and UST-533 (microsurgical linear, 7.5–13.0 MHz). In routine clinical practice, the convex neonatal probe was predominantly used for supratentorial lesions. The "hockey stick" transducer was used for spinal cord procedures. The microsurgical probe was used in limited surgical approaches, including surgeries on the brainstem and medulla oblongata, as well as for small subcortical lesions and for surgeries performed in the sitting position.

Flat silicone applicators of four sizes, made of medical-grade silicone and filled with 0.9% NaCl solution, were used as echogenic landmarks. This material is characterized by biocompatibility, resistance to deformation, and stable acoustic properties. Due to their high echogenicity, the silicone applicators were clearly visualized on ultrasound as hyperechoic structures. The use of various sizes allowed the technique to be adapted to specific anatomical conditions. Small applicators were used for brainstem and spinal cord procedures, as well as for the resection of small subcortical foci, while larger ones were used for deep-seated or extensive lesions. The size and shape of the applicators could be modified according to intraoperative needs.

Unlike cottonoid patties, silicone applicators are easily distinguishable from surrounding structures with increased echogenicity, such as hemostatic materials or blood clots [2,31]. To enhance identification accuracy, a technique of displacing and returning the applicator using its attached thread was employed, allowing the surgeon to reliably distinguish it from surrounding tissues. This technique has been used in clinical practice by the senior author and proved particularly useful during the initial learning phase for young specialists.

During intraoperative ultrasonography (IOUS), it is recommended to perform scanning in two anatomical planes simultaneously whenever possible. This approach allows for more accurate three-dimensional orientation of the pathological focus relative to the anatomical structures of the brain and spinal cord, significantly enhancing the precision of surgical navigation. The most informative planes for most supratentorial lesions are the coronal and sagittal planes, while axial scanning provides optimal orientation for pathology of the insular region. For lesions of the cerebellum, brainstem, and spinal cord, combinations of axial and sagittal planes are most valuable for spatial orientation.

To improve orientation efficiency, it is crucial that the angles of the ultrasound scanning planes closely correspond to physiological anatomical landmarks and align with the planes of preoperative imaging. Discrepancies in angles can lead to disorientation, especially for surgeons using the technique for the first time. The introduction of echogenic markers in the form of medical silicone applicators or balloons filled with saline significantly simplifies this process. Due to their clear acoustic properties and precise positioning capability, these applicators produce stable echo signals that are easily correlated with preoperative MRI and 3D reconstruction results, thereby reducing the risk of errors in intraoperative navigation.

The surgeon must be proficient in both traditional anatomical topography of the brain and its ultrasonic representation. The use of IOUS with silicone balloons as echogenic landmarks allows for more reliable identification of the surgical trajectory, minimizes damage to functionally significant tissues, and increases the accuracy of resection. High-quality additional imaging modalities also play an important role—preoperative magnetic resonance imaging (3 Tesla, slice thickness 1 mm), preoperative three-dimensional reconstructions (e.g., using OsiriX software), and intraoperative echo signals from silicone applicators—which together form a comprehensive orientation system.

In practical work, planning of the surgical approach begins at the preoperative stage: 3D reconstruction is performed using OsiriX, correlating the pathological focus with cortical gyri, sulci, and major blood vessels. The construction of vascular network reconstructions is particularly important because, unlike parenchymal structures, superficial veins are not subject to shift due to cerebrospinal fluid loss and maintain stable topographic positions. This makes them reliable landmarks for IOUS and the use of silicone applicators.

For optimal transmission of ultrasound waves, the surgical cavity must be completely filled with saline, ensuring maximum effective acoustic coupling between the transducer and the brain tissue. Silicone applicators, filled with the same solution, become part of a unified medium and produce a clear, reproducible echo signal. The patient's position is also important: it should be adjusted to maintain even distribution of the saline and continuous irrigation of the surgical site throughout the procedure.

Thus, the combination of multiplanar ultrasonography, high-resolution preoperative reconstructions, and the use of silicone applicators as echogenic markers creates a reliable and dynamic intraoperative navigation system. This ensures precise definition of the surgical trajectory, reduces the risk of damage to healthy tissue, and significantly enhances the safety and radicalness of interventions for complex intraparenchymal lesions.

Characteristics of Saline-Filled Silicone Applicators/Balloons:

Medical-grade silicone is biocompatible and inert;

Stable echogenicity due to filling with saline solution;

Variety of shapes and sizes, allowing for individual adaptation;

Clear visualization; easily displaced and identified by manipulating the attached thread;

Minimal trauma; smooth surface reduces the risk of adhesion and mechanical damage;

Versatile: applicable for supratentorial, brainstem, and spinal lesions.

### 3. Results

This paper presents a technique developed by the authors, illustrated by clinical observations of patients with pathological formations of varying nature and different localizations within the cranial cavity. All cases were selected from a large series of surgical interventions performed by the lead author using intraoperative ultrasonography, where the key navigational element was the use of silicone applicators or balloons filled with saline.

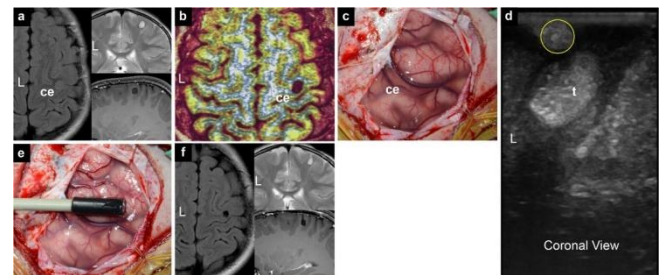
The presented clinical examples reflect both the basic principles of the method's application and its efficacy in solving various technical and navigational tasks. The silicone applicators served as echogenic landmarks, generating stable ultrasound signals and allowing the surgeon to correlate the intraoperative image with preoperative MRI data and three-dimensional reconstructions with high precision. Thus, the technique provided clear spatial orientation within the surgical field, even in the presence of significant shift or deformation of brain structures due to cerebrospinal fluid loss or partial tumor resection.

Furthermore, the analysis of clinical cases demonstrated that the use of saline-filled silicone balloons minimizes the risk of errors in defining the boundaries of a pathological focus, particularly in areas of high functional significance—cortical zones adjacent to pathways, as well as near major

vessels. In these scenarios, conventional ultrasonography may yield limited results due to uneven distribution of the acoustic signal, whereas the introduction of echogenic markers creates additional stable reference points.

Thus, the presented observations demonstrate the practical value and broad capabilities of the described technique. It enhances the accuracy of intraoperative navigation, improves control over the extent of resection, reduces the likelihood of residual tumor mass retention, and increases the overall safety of the intervention. Systematic experience with its application confirms that this approach can be considered a reliable tool in the arsenal of modern neurosurgical technologies.

#### Case 1



(a) Preoperative axial FLAIR images, coronal T2-weighted, and sagittal contrast-enhanced T1-weighted MRI revealed a small, non-encapsulated subcortical lesion in the upper portion of the right precentral gyrus.

(b) Based on the anatomy of the cortical veins and the lesion's location, a right frontoparietal craniotomy was planned using preoperative 3D reconstruction with OsiriX software [17].

(c) After dural opening, the cortical surface showed no visible signs of an underlying pathological process.

(d, e) For intraoperative navigation, an ultrasound transducer was placed on the cortical surface alongside a small saline-filled silicone applicator, enabling the use of the advanced iUS-navigation technique. The coronal scan visualized a well-defined hyperechoic tumor (t) and the echogenic signal from the silicone applicator (circled), allowing for precise determination of the optimal entry point. A minimal cortical incision of 5 mm in length provided sufficient exposure for surgical access, enabling gross-total resection of the tumor without postoperative neurological deficit.

(f) Follow-up axial FLAIR, coronal T2-weighted, and sagittal post-contrast T1-weighted MRI images obtained 3 months postoperatively showed no evidence of residual or recurrent tumor (L — left side, ce — central sulcus).

**Figure 1**

A 9-year-old female patient was admitted with a two-month history of epileptic seizures. Magnetic resonance imaging of the brain revealed an intracerebral lesion located in the upper portions of the right precentral gyrus. Given the clinical manifestations and the topography of the lesion, a decision was made to proceed with surgical treatment.

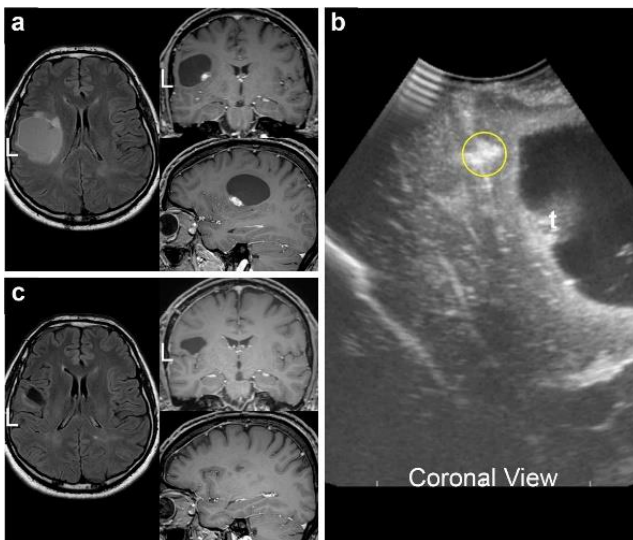
The surgery was performed with the patient in the supine position, undergoing a right frontoparietal craniotomy. To ensure precise intraoperative navigation and optimize ultrasound control, the technique utilizing saline-filled silicone applicators was employed. The applicators were placed within the surgical site in such a way as to create clear echogenic landmarks, allowing for highly reliable differentiation of the tumor boundaries from adjacent functionally significant areas of the cortex and subcortical structures. The use of this

technique significantly improved the quality of visualization and reduced the risk of resection beyond the pathological focus.

Radical tumor removal was performed, achieving gross total resection. Histopathological examination confirmed the diagnosis of a Grade II oligodendroglioma according to the World Health Organization (WHO) classification. Due to the favorable histological variant and complete tumor removal, the patient did not receive adjuvant therapy.

The postoperative course was uneventful. Neurological status remained stable, and epileptic seizures ceased completely. Follow-up magnetic resonance imaging performed 3 months after the intervention showed no signs of residual or recurrent tumor, confirming the effectiveness of the applied technique (Fig. 1 a–f).

### Case 2



(a) Preoperative axial FLAIR images, as well as coronal and sagittal T1-weighted MRI images with contrast enhancement, revealed a pathological lesion with marked contrast uptake accompanied by a large cystic component, localized in the region of the left transverse parietal gyrus. (b) After performing a left pterional craniotomy and opening the dura mater, arachnoid dissection was carried out, exposing the posterior portion of the Sylvian fissure. A silicone applicator filled with saline was placed into the superior part of the Sylvian cistern, between the insular cortex and the transverse parietal gyri, to serve as an echogenic landmark. Application of the modified intraoperative ultrasound (ioUS) technique with the applicator allowed clear visualization of the spatial relationship of the tumor (t), which included a hyperechoic solid and hypoechoic cystic component, and the hyperechoic signal from the silicone applicator (circled) in the coronal projection. After determining the optimal surgical trajectory, the tumor was removed through the posterior part of the Sylvian fissure. (c) Follow-up axial FLAIR images, as well as coronal and sagittal post-contrast T1-weighted MRI scans 3 months after the procedure, revealed no residual or recurrent tumor (L — left side).

**Figure 2**

A 51-year-old patient was admitted with complaints of sudden episodes of speech arrest that had been occurring for one month. Magnetic resonance imaging (MRI) of the brain revealed a space-occupying lesion localized in the region of the transverse gyri of the left parietal lobe.

The surgical procedure was performed with the patient in the supine position. A left pterional craniotomy was carried

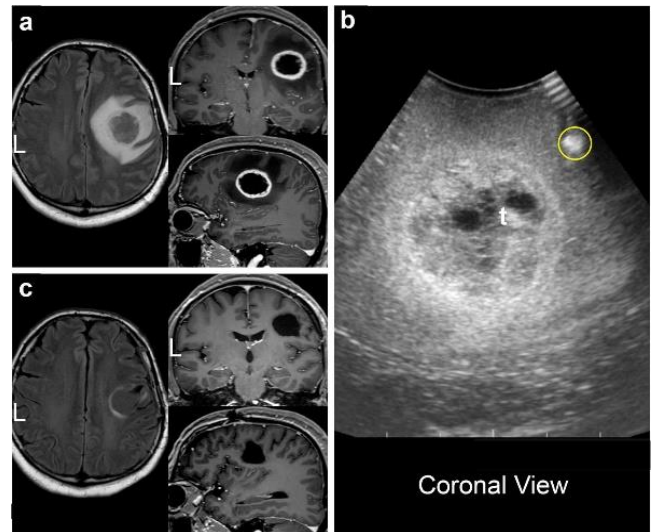
out to access the pathological focus. To optimize intraoperative navigation and improve the accuracy of ultrasound monitoring, a technique involving silicone applicators filled with saline was used. The applicators were placed in the surgical field as echogenic markers, which allowed clear identification of the tumor boundaries and differentiation of its cystic and solid components.

Tumor removal was performed in stages: first, the cystic component was opened and evacuated, followed by resection of the solid part of the tumor. Thanks to the use of this technique, a gross total resection of the lesion was achieved while preserving functionally significant structures and without postoperative neurological deficit.

Histopathological examination confirmed the diagnosis of ganglioglioma (WHO Grade I). Given the complete resection and favorable prognosis, no adjuvant therapy was administered.

In the postoperative period, the patient remained in satisfactory condition, and epileptic seizures did not recur. Follow-up MRI at 3 months confirmed complete tumor removal with no evidence of recurrence (Fig. 2a–c).

### Case 3



(a) Preoperative axial FLAIR images, as well as coronal and sagittal contrast-enhanced T1-weighted MRI scans, demonstrated a contrast-enhancing tumor located in the deep portions of the right precentral gyrus, extending into the centrum semiovale, with significant peritumoral edema. (b) After performing a right fronto-parietal craniotomy and opening the dura mater, the middle portion of the precentral sulcus was widely exposed. A silicone applicator filled with saline was placed into the sulcus, after which intraoperative ultrasonography was performed. This technique allowed visualization of the spatial relationship between the hyperechoic tumor (t), which contained hypoechoic central areas, and the echogenic signal from the silicone applicator (circled) in the coronal projection. This provided precise determination of the optimal surgical trajectory through the precentral sulcus, enabling gross total resection of the tumor. (c) Follow-up axial FLAIR images, as well as coronal and sagittal post-contrast T1-weighted MRI scans obtained 3 months after surgery, revealed no residual or recurrent tumor (L — left side).

**Figure 3**

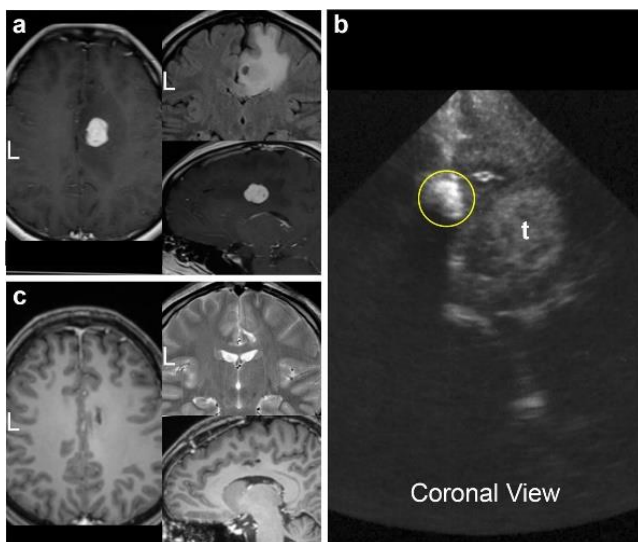
A 49-year-old man was admitted with complaints of mild left-sided hemiparesis that had persisted for one week.

Magnetic resonance imaging (MRI) revealed a deeply located tumor in the region of the right precentral gyrus. The patient underwent surgery in the supine position with a right fronto-parietal craniotomy.

Using intraoperative ultrasonography guided by a silicone applicator filled with saline, the optimal surgical trajectory was clearly determined. This enabled gross total resection of the tumor. Histopathological examination confirmed the diagnosis of glioblastoma (WHO Grade IV).

In the postoperative period, there was marked neurological improvement with regression of the preoperative hemiparesis. After discharge, the patient underwent adjuvant chemoradiotherapy. Follow-up MRI at 3 months demonstrated no residual or recurrent tumor, and the patient remained neurologically intact (Fig. 3a–c).

#### Case 4



- (a) Preoperative axial and sagittal contrast-enhanced T1-weighted MRI scans, as well as coronal FLAIR images, revealed a contrast-enhancing tumor in the middle third of the right cingulate gyrus, accompanied by pronounced perilesional edema.
- (b) The middle portions of the corpus callosum and cingulate gyrus were exposed via the right anterior interhemispheric approach. A silicone applicator filled with saline was placed into the interhemispheric space at the level of the cingulate gyrus, after which intraoperative ultrasonography was performed. In the coronal projection, the relatively hyperechoic tumor (t) and the hyperechoic contour of the silicone applicator (circled) were clearly visualized. The use of this technique allowed determination of the optimal surgical trajectory and enabled a precise, minimally invasive incision within the cingulate gyrus, ensuring radical tumor removal without the development of postoperative deficits.
- (c) Follow-up MRI scans (axial and sagittal contrast-enhanced T1-weighted images, as well as coronal FLAIR images) obtained 3 months postoperatively demonstrated no signs of residual or recurrent tumor. It should be noted that the marked preoperative edema had completely resolved after total resection, highlighting that not every alteration visualized on FLAIR should be interpreted as tumor tissue requiring resection (L — left side).

**Figure 4**

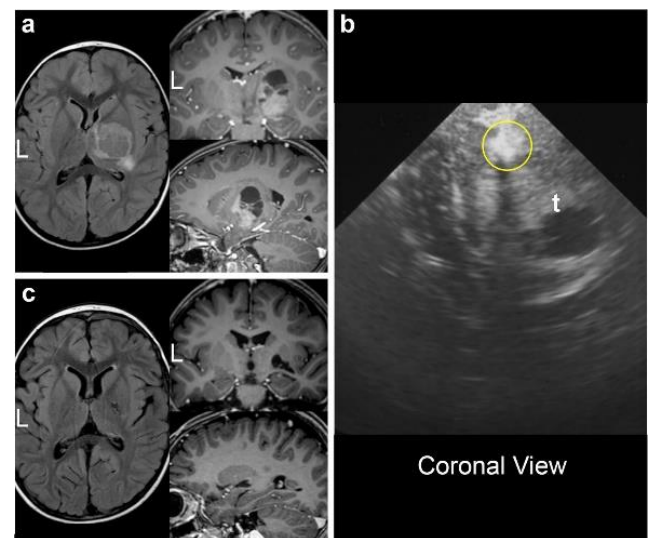
A 22-year-old female patient was admitted with complaints of epileptic seizures that had been occurring over the past month. MRI revealed a tumor localized in the region

of the right cingulate gyrus. With the patient in the supine position, surgical access was achieved via a right anterior interhemispheric approach, which allowed exposure of the cingulate gyrus.

Using intraoperative ultrasonography guided by a silicone applicator filled with saline, the surgical trajectory was precisely determined, enabling radical removal of the lesion through a precision incision within the cingulate gyrus.

Histopathological examination confirmed the diagnosis of subependymal giant cell astrocytoma (WHO Grade I). The postoperative period was uneventful, and the patient was discharged without the need for adjuvant therapy. Since surgery, no epileptic seizures have recurred. Follow-up MRI at 3 months demonstrated no evidence of residual tumor tissue or recurrence within the operative cavity (Fig. 4a–c).

#### Case 5



- (a) Preoperative axial FLAIR images, as well as coronal and sagittal contrast-enhanced T1-weighted MRI scans, demonstrated a right-sided tumor of the posterior globus pallidus without contrast enhancement, associated with compression of the internal capsule.
- (b) After performing a right pterional craniotomy and proximal dissection of the Sylvian fissure, a silicone applicator filled with saline was placed into its opercular segment, followed by intraoperative ultrasonography. In the coronal plane, the hyperechoic applicator (circled) and the tumor (t), which displayed a combination of hypoechoic cystic and hyperechoic solid components, were clearly visualized. Based on their topographic relationship, the optimal surgical trajectory was determined. Additionally, a dominant lateral lenticulostriate artery supplying the tumor was identified. Its course was traced by means of intraparenchymal dissection, enabling safe access to the lesion. Gross total resection was achieved.
- (c) Follow-up MRI scans (axial FLAIR, coronal and sagittal contrast-enhanced T1-weighted images) obtained 3 months postoperatively revealed no residual or recurrent tumor. Restoration of the normal anatomical position of surrounding structures was also noted, allowing reliable confirmation of the tumor's origin from the posterior globus pallidus (L — left side).

**Figure 5**

A 5-year-old girl was admitted with a two-week history of mild left-sided hemiparesis. Magnetic resonance imaging (MRI) revealed a tumor located in the right posterior globus pallidus. With the patient in the supine position, a right

pterional craniotomy was performed. Using intraoperative ultrasonography guided by placement of a silicone applicator filled with saline, the most accurate surgical trajectory was determined, allowing gross total resection of the tumor.

Histopathological evaluation was initially challenging; however, the lesion was ultimately classified as a primitive neuroectodermal tumor, and the patient subsequently underwent adjuvant radiotherapy. In the postoperative period, marked regression of the preexisting hemiparesis was observed. Follow-up MRI at 3 months showed no evidence of residual or recurrent tumor.

Long-term surveillance over 14 years also demonstrated no recurrence, suggesting that the initial histopathological diagnosis was likely erroneous (Fig. 5a–c).

### Anterior transcallosal approaches

In anterior transcallosal approaches, the standard site of callosotomy is not universal and must be determined individually for each patient. Such an individualized selection minimizes the risk of postoperative morbidity by maximizing preservation of the corpus callosum.

In cases where anterior interhemispheric approaches are employed for deeply located lesions (intraventricular, thalamic, deep nuclear tumors, etc.), the first silicone applicator filled with saline can be placed into the interhemispheric fissure above the intended site of callosotomy. Using intraoperative ultrasonography, this technique allows precise clarification of the exact location and angle of the callosotomy. This ensures access to the pathological focus with the smallest possible incision of the corpus callosum.

In rare cases, after the callosotomy has been performed, a second applicator may be placed into the lateral ventricle for additional verification of the surgical trajectory, depending on the location of deep-seated lesions that are not visible from the ventricular surface. The application of intraoperative ultrasonography with silicone applicators makes it possible to perform a callosotomy of minimal extent, thereby reducing the risk of operative trauma and postoperative morbidity.

In our practice, this approach has demonstrated high effectiveness in determining the most precise site for callosotomy. The use of silicone applicators filled with saline, in combination with intraoperative ultrasonography, has proven especially valuable for accurate localization of the corpus callosum incision. The first implementation of this method for performing callosotomy was introduced by the senior author, and at present this direction remains one of the most significant applications of the technique.

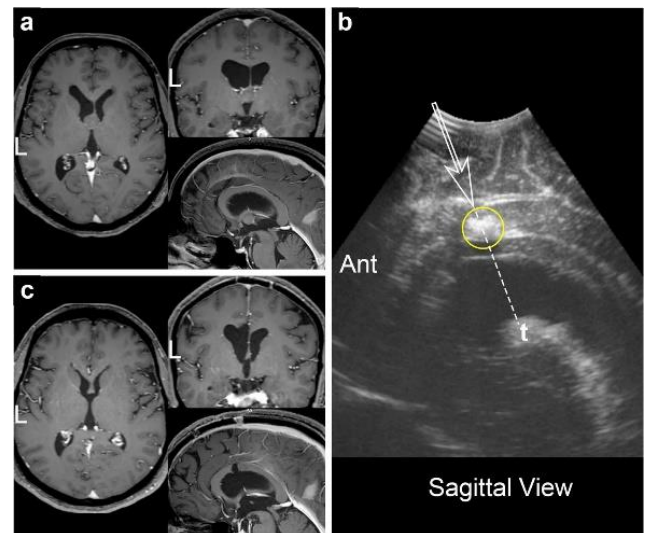
### Case 6

A 44-year-old female patient presented with severe headaches that had begun two months prior to hospitalization. MRI revealed a cystic lesion localized in the region of the third ventricle.

With the patient in the supine position, a right anterior frontal interhemispheric approach was performed, exposing the corpus callosum. The most accurate point of callosotomy

and the optimal angle of incision were determined using intraoperative ultrasonography in combination with a silicone applicator filled with saline. This allowed a limited callosotomy of only 5 mm in length and enabled total removal of the lesion.

Histopathological examination confirmed the diagnosis of a colloid cyst. The postoperative course was uneventful. Follow-up MRI performed 3 months later confirmed complete removal of the lesion without evidence of recurrence (Fig. 6a–c).



(a) Preoperative axial, coronal, and sagittal contrast-enhanced T1-weighted MRI scans demonstrated a non-enhancing cystic lesion in the region of the third ventricle consistent with a colloid cyst, as well as enlargement of the left lateral ventricle.

(b) The corpus callosum was exposed via a right anterior frontal interhemispheric approach. A small silicone applicator filled with saline was placed at the intended site of callosotomy, followed by intraoperative ultrasonography in the sagittal plane. Based on the spatial relationships between the hyperechoic applicator (circled), the foramen of Monro, and the hyperechoic lesion (t), the most precise surgical trajectory was determined (arrow). Through a 5-mm callosotomy, the lesion was accessed and completely removed.

(c) Follow-up axial, coronal, and sagittal contrast-enhanced T1-weighted MRI scans obtained 3 months postoperatively confirmed gross total removal of the lesion without evidence of recurrence (L — left; Ant — anterior).

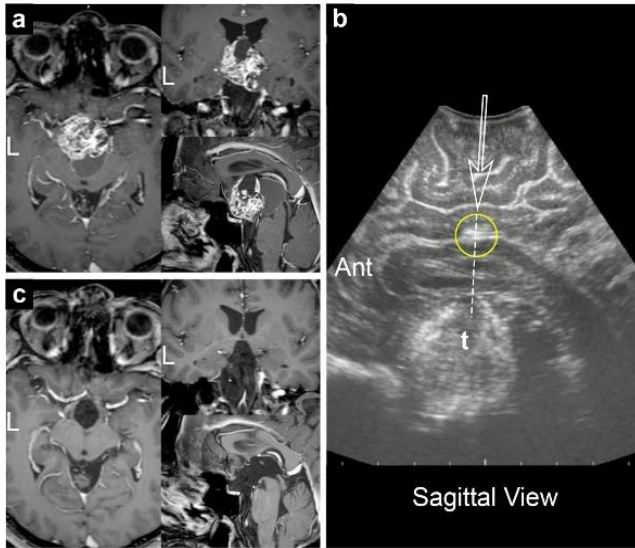
**Figure 6**

### Case 7

A 41-year-old male patient presented with complaints of amnesia, visual field deficits, and pronounced polydipsia. MRI revealed a suprasellar lesion. With the patient in the supine position, a right posterior frontal interhemispheric approach was performed, and the surgical trajectory was visualized using intraoperative ultrasonography (ioUS) with guiding silicone applicators filled with saline. During this procedure, a partial tumor resection was carried out.

At the next stage, through a combined right pterional approach, gross total tumor resection was achieved. Histopathological examination revealed an adamantinomatous craniopharyngioma (WHO grade I). No adjuvant therapy was required. The postoperative course was uneventful.

Follow-up MRI performed at 3 months demonstrated no residual or recurrent tumor (Fig. 7a–c).



(a) Preoperative axial, coronal, and sagittal T1-weighted post-contrast MRI scans demonstrated a contrast-enhancing suprasellar lesion extending into the third ventricle. Imaging findings were consistent with a craniopharyngioma.

(b) Via a right posterior frontal interhemispheric approach, the corpus callosum was exposed. To delineate the area of callosotomy, a small silicone applicator filled with saline was used, followed by intraoperative ultrasonography (ioUS). On the sagittal image, the spatial relationship between the hyperechoic silicone applicator (circled), the foramen of Monro, and the hyperechoic tumor (t) was identified. The surgical trajectory (arrow) was chosen to optimally access the anterior portion of the lesion, and a callosotomy was performed posterior to the foramen of Monro. Through an approximately 5-mm callosotomy, the tumor was visualized and partially resected.

The remaining portion of the tumor was completely resected through a combined right pterional approach.

(c) Follow-up axial, coronal, and sagittal T1-weighted post-contrast MRI scans obtained 3 months postoperatively demonstrated no residual or recurrent tumor (L — left; Ant — anterior).

**Figure 7**

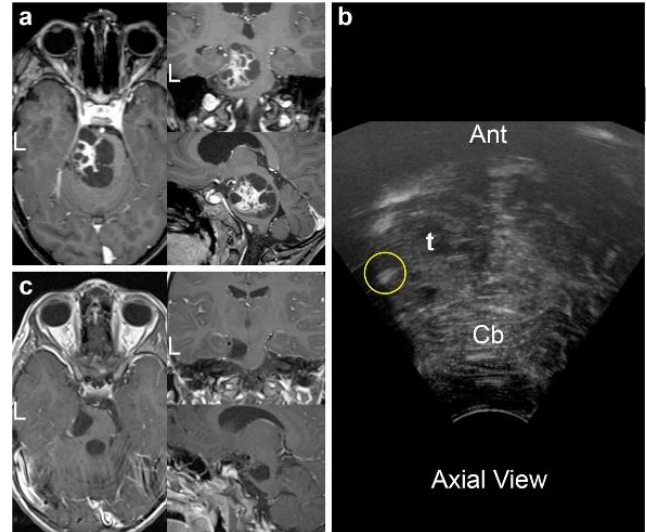
### Brainstem and spinal cord lesions

The brainstem and spinal cord are characterized by high tissue density and contain numerous complex and vital structures. Even millimetric injury to normal tissue can result in a significant increase in morbidity. Therefore, every surgical step must be carefully planned and executed with the utmost precision to preserve healthy tissue. This is especially important in patients with deeply located lesions lacking a visible projection on the brain surface; in such cases, the use of intraoperative ultrasonography (ioUS) with guiding silicone applicators filled with saline allows for minimization of normal tissue damage [24].

After adequate exposure of the brainstem, a silicone applicator can be placed at the presumed entry point, considered a relatively safe zone, and ioUS can then be performed. Once the optimal entry point and the most favorable trajectory have been determined, a small incision can be made with the tip of bipolar forceps and carefully expanded parallel to the major white matter fiber tracts [24].

Intramedullary spinal cord lesions can be exposed, depending on their size, through hemilaminoplasty [18]. The precise location of the lesion and the appropriate level of dural opening are determined using ioUS with silicone applicators, which makes it possible to assess whether the extent of the hemilaminoplasty is sufficient. Once the level of the lesion is identified, access can be obtained primarily through the posterior median sulcus or, in selected cases, through the posterior intermediate sulcus and the dorsal root entry zones.

### Case 8



(a) Preoperative axial, coronal, and sagittal T1-weighted post-contrast MRI scans demonstrated a small increase in the size of a left-sided multicystic contrast-enhancing pontine tumor. With the patient in the lateral position, the lateral surface of the pons was visualized through a left lateral suboccipital retrosigmoid approach. To identify the location of the middle cerebellar peduncle, a small silicone applicator filled with saline was placed, followed by intraoperative ultrasonography (ioUS).

(b) On the axial image, the hyperechoic silicone applicator (circled) and the tumor (t), consisting of hypoechoic cystic components and relatively hyperechoic solid fragments, were visualized. Based on the spatial relationship between the applicator and the tumor, a precise incision was made through the middle cerebellar peduncle parallel to the transverse pontine fibers, enabling radical tumor removal.

(c) Follow-up axial, coronal, and sagittal T1-weighted post-contrast MRI scans obtained 3 months postoperatively demonstrated no residual or recurrent tumor (L — left; Ant — anterior; Cb — cerebellum).

**Figure 8**

A 4-year-old boy was admitted with right-sided hemiparesis. MRI revealed a left-sided multicystic pontine lesion. At another institution, an open biopsy was performed via a left pterional approach, after which a diagnosis of high-grade tumor was made, and the patient was started on adjuvant chemotherapy.

Despite ongoing treatment, the hemiparesis progressed, and follow-up MRI demonstrated minimal enlargement of the lesion. Consequently, adjuvant radiotherapy was planned, and the patient was referred to us for a second opinion. Despite the prior diagnosis of a high-grade tumor, the minimal increase in size after biopsy raised concerns about a possible error in the initial histopathological report.

Given the slight growth of the lesion and the progression of symptoms, we recommended microsurgical resection. With the patient positioned laterally, the lesion was removed via a left lateral suboccipital retrosigmoid approach, employing intraoperative ultrasonography (ioUS) with guiding silicone applicators filled with saline. Postoperatively, the patient exhibited no neurological deficit.

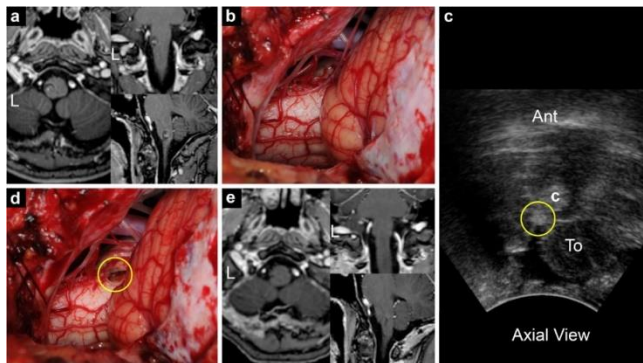
Histopathological examination revealed a pilocytic astrocytoma (WHO grade I), and no adjuvant therapy was administered. Follow-up MRI at 3 months showed no evidence of residual or recurrent tumor (Fig. 8a–c).

### Case 9

A 31-year-old man was admitted to our clinic with complaints of right-sided hemihypoesthesia persisting for 3 weeks. Preoperative MRI demonstrated a left-sided lesion of the medulla oblongata.

Through a left anterolateral supracondylar approach with the patient in the lateral position, radical resection of the lesion was performed using intraoperative ultrasonography (ioUS) with guiding silicone applicators filled with saline. No postoperative neurological deficits were observed.

Histopathological examination confirmed the diagnosis of cavernoma. Follow-up MRI at 3 months revealed no residual or recurrent lesion, and the patient remained neurologically intact (Fig. 9a–e).



- (a) Preoperative axial, coronal, and sagittal T1-weighted post-contrast MRI scans demonstrated a hemorrhagic left-sided medullary lesion consistent with a cavernoma.
- (b) The lateral surface of the medulla oblongata was exposed through a left anterolateral supracondylar approach with the patient in the lateral position.
- (c) To refine the surgical trajectory, a small silicone applicator filled with saline was placed into the retro-olivary sulcus, followed by intraoperative ultrasonography (ioUS). On the axial plane, the silicone applicator (circled) and the relatively hyperechoic lesion (c) were visualized. Their spatial relationship allowed determination of the optimal surgical route through the retro-olivary sulcus.
- (d) A 4-mm incision through the retro-olivary sulcus, made perpendicular to the fibers, enabled complete removal of the lesion.
- (e) Follow-up axial, coronal, and sagittal T1-weighted post-contrast MRI scans obtained 3 months postoperatively showed no residual lesion or recurrence (L — left; Ant — anterior; To — tonsil).

**Figure 9**

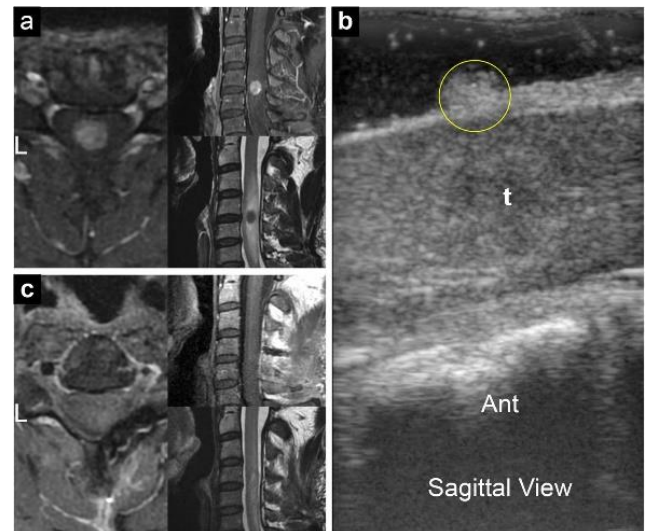
### Case 10

A 34-year-old man was admitted with complaints of numbness in the left arm persisting for 1 month. Preoperative

MRI revealed an intramedullary lesion of the cervical spinal cord at the C4–C5 vertebral level.

With the patient in the prone position, a left-sided C4–C5 hemilaminoplasty was performed. Using intraoperative ultrasonography (ioUS) with guiding silicone applicators filled with saline, the most accurate surgical trajectory was determined. Through the posterior median sulcus, radical resection of the lesion was achieved without postoperative neurological deficits.

Histopathological examination confirmed the diagnosis of ependymoma; therefore, adjuvant therapy was not required. Follow-up MRI at 3 months demonstrated no residual or recurrent tumor (Fig. 10a–c).



- (a) Preoperative axial and sagittal MRI scans with T1-weighted post-contrast and sagittal T2-weighted sequences revealed an intramedullary lesion at the C4–C5 vertebral level.
- (b) After left-sided C4–C5 hemilaminoplasty and dural opening, a small silicone applicator filled with saline was placed over the posterior median sulcus, followed by intraoperative ultrasonography (ioUS). On the sagittal plane, the spatial relationship between the silicone applicator (circled) and the lesion (t) was visualized. Based on their relative positioning, the most precise surgical trajectory through the posterior median sulcus was defined, enabling radical resection of the lesion.
- (c) Follow-up MRI scans obtained 3 months postoperatively in axial and sagittal views with T1-weighted post-contrast and sagittal T2-weighted sequences revealed no residual or recurrent tumor (L — left; Ant — anterior).

**Figure 10**

## 4. Discussion

The success of surgical intervention largely depends on the accurate determination of the anatomical location of the lesion and the planning of the optimal approach to it. The most appropriate site for craniotomy may be determined using preoperative imaging modalities, 3D reconstructions, neuronavigation systems, and analysis of the spatial relationship between topographic landmarks and the lesion [13,17,19,23, 37,38,40,44]. Since the cortical exposure zone is limited, achieving precise anatomical orientation during

surgery is not always a simple task. Gyri, sulci, and the cortical vascular network can serve as landmarks for defining the projection of superficial lesions onto the cortex [13,17,23,40].

However, access to subcortical or deeply located lesions, which leave no trace on the cortical surface, remains a challenging task for neurosurgeons. Over the past two decades, a wide range of preoperative radiological imaging modalities (MRI, CT, DSA, PET, fMRI, etc.) have been increasingly applied in neurosurgical practice for intraoperative navigation [3,51]. These methods require topographic correlation of the patient's position during surgery with preoperative imaging and provide anatomical orientation throughout the surgical procedure.

When dealing with deeply located or subcortical lesions, intraoperative ultrasonography (ioUS) with guiding silicone applicators or balloons filled with saline has proven particularly useful, as it enables accurate determination of the optimal surgical trajectory and minimizes damage to normal tissue.

During surgery, cerebrospinal fluid drainage, gravity, patient positioning, and anesthetic effects may cause brain shift and reduce the accuracy of neuronavigation systems [32,33,39]. Particularly in cases where modern neuronavigation systems lose precision, intraoperative ultrasonography (ioUS) can be easily and safely employed to generate a three-dimensional configuration of the lesion, providing superior anatomical orientation during surgery compared to other navigation methods. ioUS enables tumor visualization in multiple planes from different angles, which is not feasible with standard navigation technologies. Moreover, due to its dynamic nature, any intraoperative anatomical deformations can be promptly detected throughout the procedure.

In 1983, Gooding and colleagues proposed the use of ioUS with hyperechoic surgical sponges soaked in saline to assess the course of dissection, the progress of resection, and the extent of tumor removal [14]. In the same year, Voorhies and colleagues described the use of ioUS with a small silicone applicator filled with saline to determine the spatial relationship between the tumor and surface topography, as well as to select the optimal surgical trajectory angle. They also suggested using a biopsy catheter under ultrasound guidance for tract marking and dissection guidance [47]. The following year, a paper was published describing the use of a silicone applicator in subcortical tumors to verify the surgical approach in cases where the tumor was not encountered at the expected depth [46].

Despite these reports, the basic principles of applicator use and their primary purpose were limited merely to trajectory verification for locating subcortical tumors inaccessible during the initial surgical exploration [28]. Although the use of such applicators as acoustic markers had previously been described by Voorhies and colleagues [46], the method never became widespread and was gradually almost forgotten. We have revived and refined the use of silicone applicators as acoustic markers in routine neurosurgical practice, which allows for safe and precise orientation when dealing with deeply located or subcortical lesions.

## 5. Comparison of ioUS with Silicone Applicators, Neuronavigation, and Intraoperative MRI

In our department, all modern intraoperative technologies are available, including intraoperative MRI (ioMRI), intraoperative ultrasonography (ioUS), ICG, 5-ALA, O-arm, neuronavigation, and neuromonitoring. We apply these tools during surgery, taking into account their capabilities and limitations, in order to achieve the best surgical outcomes.

We have found that neuronavigation has certain limitations compared to ioUS. While ioUS provides true real-time imaging and is not affected by brain shift, neuronavigation relies on preoperative imaging and does not offer continuous real-time guidance. Thus, intraoperative brain shift remains a major issue when using neuronavigation, reducing its accuracy and reliability during surgery.

To overcome this limitation, some groups have developed navigation systems integrated with ultrasound [6,10,15,20, 27,28]. This is an effective technique for resolving problems related to intraoperative brain shift. However, the resolution of such systems was lower than that of our intraoperative ultrasound system. Since high resolution is critically important for ioUS, and our technique of intraoperative ultrasound with guiding silicone applicators provides full real-time visual support, the senior author preferred this method when working with intraparenchymal CNS lesions.

Nevertheless, standard neuronavigation remains the method of choice for craniotomies and skull base surgeries, since most bony structures remain in place throughout the operation, providing stable anatomical landmarks.

In our opinion, comparing intraoperative ultrasound (ioUS) with intraoperative MRI (ioMRI) is inappropriate for several reasons. The use of ioMRI requires additional infrastructure, MRI-compatible instruments, and specific patient positioning. One of the key advantages of our ioUS technique with guiding silicone applicators is that it requires no additional preparation or specialized instruments. Only silicone applicators, which are used in every case, and an ultrasound machine—available in almost any hospital—are necessary.

Furthermore, the use of ioMRI for real-time navigation is not feasible. Typically, ioMRI is employed to assess residual tumor during surgery and provides higher accuracy compared to ioUS. However, even with all technological advancements, ioMRI cannot identify all residual tumor tissue or reliably differentiate edema from tumor. Repeated use of ioMRI is time-consuming and inconvenient, particularly when contrast agents are used for the first scan. In contrast, our technique can be repeated at any time at the surgeon's discretion and provides the most valuable real-time navigation.

If ioUS is compared to a car, ioMRI can be likened to an airplane. Both are necessary, but the car is used daily and is simple to operate, whereas the airplane is needed only occasionally and is more complex to use. There are certain "distances" that can only be covered by a car, only by an airplane, or by both. Similarly, we may use ioMRI alone, ioUS alone, or a combination of both methods in selected cases.

Any neurosurgeon familiar with ultrasound imaging and able to integrate 3D MRI data with surgical anatomy can master the ioUS technique with guiding silicone applicators within a few minutes. For surgeons without prior ultrasound experience, assistance from colleagues in the radiology department may be helpful during the initial training phase. However, once the technique is mastered, we strongly recommend that intraoperative ultrasound examination be performed by the neurosurgeon conducting the operation.

It is important to note that the use of ioUS does not increase surgical time, while it significantly improves both accuracy and safety. Nevertheless, ioUS has certain limitations, primarily related to the operator and technical execution, such as artifacts, use of inappropriate accessories, insufficient skills, or lack of experience [29,34]. In selected cases, the use of ioMRI or contrast-enhanced ultrasound may yield more accurate results, particularly for assessing residual tumor during surgery [10,30,35].

Thanks to its ability to provide continuous real-time imaging and immunity to brain shift and intraoperative parenchymal changes, ioUS plays a key role in our practice as an intraoperative imaging tool. Moreover, it is relatively inexpensive and available in almost every hospital, making it easy to implement in neurosurgical operating rooms.

As demonstrated in this study, the ioUS technique with guiding silicone applicators allows for safer and more precise surgery. It promotes maximal preservation of healthy parenchyma during intervention and, consequently, leads to better clinical outcomes with reduced morbidity. In addition to its ease of use and relatively low cost, we observed the high speed, reliability, and exceptional utility of this technique.

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