Chapter

Usefulness of Intraoperative 2D-Ultrasound in the Resection of Brain Tumors

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Abstract

The surgical approach to brain tumors often uses preoperative images to visualize the characteristics of pathology, guiding the surgical procedure. However, the usefulness of preoperative images during the surgical procedure is altered by the changes in the brain during the surgery because of craniotomy, inflammation, tumor resection, cerebrospinal fluid (CSF) drainage, among others. For this reason, there is a need to use intraoperative imaging evaluation methods that allow the surgeon to consider these changes, reflecting the real-time anatomical disposition of the brain/tumor. Intraoperative ultrasound (iUS) has allowed neurosurgeons to guide the surgical procedure without exposing the patient to ionizing radiation or interrupting the procedure. Technological advances have made it possible to improve image quality, have smaller probes, and facilitate the use of the equipment, in addition to the introduction of new imaging modalities, such as three-dimensional images, enhanced with contrast, among others, expanding the available options. In the context of these advances, the objective of this chapter was to review the current status of the usefulness and challenges of iUS for brain tumor resection through an in-depth review of the literature and the discussion of an illustrative case.

Keywords: ultrasonography, intraoperative, navigation, neurosurgery, brain tumors

1. Introduction

Usage of ultrasound (US) for the first time for brain surgery was reported by Chandler et al. describing the surgical outcomes of 21 cases (including 18 patients with brain tumors) using two-dimensional imaging (2D-US) [1], allowing real-time visualization of the underlying anatomy and pathology during surgical performance. Since that time, the use of intraoperative ultrasound (iUS) has allowed surgeons to improve the decision-making during a surgical procedure without exposure to ionizing radiation [2]. The technology has evolved with the improvement of image quality and neuroimaging modalities, introducing smaller probes and more seamless integration with neuronavigation systems. In addition, the introduction of related imaging modalities, such as three-dimensional US (3D-US), high-frequency ultrasound (HF-US), contrast-enhanced US (C-US), and ultrasound elastography (E-US), diversified options with different advantages [3]. In the context of these advances, we review the current state of the intraoperative usefulness of 2D-US in comparison with the other modalities for the resection of brain tumors and expose our perspective of the usefulness of this method through the discussion of a case.

2. Intraoperative 2D-ultrasound in brain tumor surgery

2.1 Equipment and technical considerations

The US system uses sound waves at high frequencies (approximately greater than 20 kHz), using transducers that emit pulses at a frequency of 1–20 MHz [4]. These pulses emitted by the transducers are scattered, absorbed, or reflected depending on the acoustic properties of the brain tissue. The transducers detect wave echoes and produce a two-dimensional image based on the time intervals between the emitted pulses and the received echoes. The higher the frequency, the higher the images will be with the limitation of less tissue penetration. In the neurosurgical setting, transducers are typically used at 5–10 MHz, at depths of 2–8 cm, to ensure resolution between 500 and 1000 μm [2]. It is important to consider the existence of more advanced transducers that work at frequencies of up to 10–25 MHz and require a resolution of 100–600 μm, with the limitation that they are only useful for depths between 2 and 4 cm. Some of these devices were evaluated by Moran et al. [5], where the highest resolution integrals were obtained using the Vevo 770 and 2100 scanners [5]. However, it is important to consider the optimal choice of transducer, type, and acquisition frequency, which depends on several variables, such as tumor location, properties of the tumor, craniotomy size, surrounding anatomy, as well as surgeon preference [4, 5].

Regarding the interpretation of intraoperative cerebral US images, it is important to have certain considerations. The normal brain, sulci, falx cerebri, choroid plexus, and vessel walls are shown as hyperechoic images, where the gray matter is slightly more hypoechoic relative to the white matter, while the ventricles, cysts, and other spaces filled with cerebrospinal fluid (CSF) are hypoechoic. On the other hand, tumors are often hyperechoic due to their relatively high mass density. Tumors become more difficult to identify in the presence of peritumoral edema because this causes greater echogenicity and can make it difficult to differentiate the margins between the tumor lesion and normal brain tissue. It is important to consider this because the echogenicity of the chronic edema is unpredictable, creating a confounding factor during surgical intervention [6].

In neurosurgery, US is used during tumor resection for different purposes: tumor location and characterization (1), surgical planning (2), and evaluation of the extent of resection (3). The application of US is limited to the size of the craniotomy. The probe can be applied to the dura mater or the brain parenchyma; during imaging, care must be taken not to apply too much pressure (it would cause deformation and limit the usefulness of the image). Once a resection cavity has been established, it is possible to insert a probe into the cavity [7]. However, in case the transducer is very large, the cavity can be filled with saline solution to attach the transducer (technique described by Tormod Selbekk et al. [8]). It is preferable to position the patient such that the resection surface is horizontal with respect to gravity in order to minimize trapped air within the cavity (improve image quality). Because the size of the craniotomy plays a very important role in the selection of the size of the transducer, cases have also been described where an exclusive craniotomy for the probe has been performed [2].

2.2 Artifacts and limitations

The acquisition and interpretation of US images is due to the fact that it requires experience. Training in ultrasonography through the use of simulators or animals guided by experts is recommended. An artifact is defined as an image that does not represent the actual anatomy of the structure being viewed, which arises for a variety of reasons. Bone (a tissue with high signal attenuation) can create a shadow that decreases the signal from surrounding tissues. The attenuation coefficient of saline solution, which is often used to fill the resection cavity, is lower than that of brain tissue, thus producing a brightness artifact at the brain/saline interface and potentially impairing identification of the residual tumor. Coagulated blood or hemostatic materials may produce a brightness artifact. In addition, differences in sound conduction speed between tissues can cause geometric distortion of the image in two-dimensional US (2D-US), and the presence of saline solution (which conducts sound at a slower speed than the brain) produces an error of approximately 1.5 mm at a depth greater than 10 cm. Even temperature can change the speed of sound and thus influence image quality [8].

2D-US has several limitations, for example, the resolution of US is not uniform in all directions, depending on the depth of focus and the location of the target within the frame [9]. One of the most important limitations is the interoperator variability in the performance and interpretation of the images. Because the appearance of the tissue depends on the angle and depth of the US waves, it is difficult to compare the images with other study modalities such as magnetic resonance imaging (MRI) and computed tomography (CT). The 2D-US image is constructed from the plane perpendicular to the face of the transducer, so this plane does not usually coincide with the axial, sagittal, or coronal sections with which the surgeon is used to working.

2.3 Different ultrasound imaging modalities

There are various US modalities other than 2D-US, which offer different types of advantages with their respective limitations. Among these, the 3-dimensional US (3D-US) is useful for volumetric reconstruction of images [10, 11]. Among others, the high-frequency ultrasound (HF-US) operates at frequencies up to 25 MHz to provide higher resolution images, giving the advantage of producing more reliable demarcation of tumor margins even in peritumoral edema and previous radiotherapy settings [5, 12, 13]. During brain tumor surgery, Doppler US (D-US) is used to assess tumor vascularity and guide the extent of the surgical approach, using the Doppler effect, which is a change in frequency seen when a US wave is reflected into the transducer in order to determine the direction and speed of the blood flow [14, 15]. On the other hand, US elastography (US-E) is another imaging modality that allows to evaluate the elastic properties of the brain tissue, relating the stiffness of the tissue to a force applied to it [16]. Finally, contrast-enhanced US (CE-US) allows real-time visualization of tissue vascularization, being useful for identifying highly vascularized tumors. Unlike contrast agents for CT or MRI, CE-US contrast is composed of small gaseous microbubbles that resonate when hit by US waves, lacking the side effects and toxicities associated with other contrast media [17–19]. **Table 1** summarizes the advantages and limitations of all these modalities compared to 2D-US.

2.4 Ultrasound applications in brain tumor surgery

Intraoperative navigation has become the standard practice for initial localization and evaluation of tumor margins during resection [20]. However, navigation may be limited by changes in the arrangement of brain tissue during the procedure due to inflammation, tumor resection, CSF drainage, among other factors. For this reason, there is a need to incorporate an intraoperative procedure that allows to evaluate these changes. Different solutions have been proposed, such as intraoperative MRI, cone beam computed tomography, stereoscopic cameras, fluorescence materials, and the incorporation of computer software's [21–23]. However, the use of iUS continues to be a very attractive option compared to other modalities, due to its accessibility (low cost), minimal interruption of surgery, and absence of radiation. In this context, the iUS has three applications that will be discussed in detail: (1) intraoperative navigation, (2) evaluation of extent of resection, (3) and brain-shift monitoring and compensation.

2.5 Intraoperative navigation

Using an intraoperative image allows to accurately assess the location of the tumor and identify the surrounding structures. As mentioned earlier, each of the modalities has its advantages and limitations for these applications. A study by Hammoud et al. evaluated the efficacy of iUS in locating and defining tumor borders and in assessing the extent of their resection, showing that the borders were well defined in 83.3% and moderately defined in 16%, in all patients the extent of the resection was well defined (measured by postoperative MRI) [24]. Moreover, Hammoud MA and his group observed that the extent of resection was poorly defined in the patients whose pathology showed radiation effects and recurrent tumors. Therefore, the iUS provides greater fidelity in cases of primary resection compared to recurrent tumors with previous surgery and/or radiation [25], a phenomenon possibly explained by the greater echogenicity of the edema, scar tissue (gliosis), and post-radiation necrosis [26]. On the other hand, beyond the evaluation of the borders, US has proven to be useful in demonstrating the relationship between the appearance of brain tissue on intraoperative ultrasonography and pathological grade of cerebral glioma, managing to differentiate low-grade gliomas (calcifications and hyperechoic), in contrast to high-grade gliomas that usually present changes due to necrosis [27]. If what is desired is to improve the identification of the tumor volume, US can be combined with MRI, improving the visualization beyond the margins visualized with MRI contrast (gadolinium), helping to differentiate the tumor from the edema visible on T2-weighted images [28]. In addition, US is comparable to CT in stereotactic guidance for taking brain biopsies, according to diagnostic yield rate [29].

The utility of 3D-US was first evaluated by Unsgaard et al. in a series of 28 patients for the resection of primary and metastatic brain tumors, showing that this modality gives a good delineation of metastases and the solid part of tumor (gliomas) before starting the resection. When comparing tumor identification using 3D-US versus pathologic diagnosis, biopsies taken from the edge of the tumor revealed more than 70% correlation in low-grade and anaplastic astrocytoma's,

Imaging modality	Advantages	Limitations
2D-US	• Fast image acquisition • Relatively easy to use • Equilibrium between resolution and penetration • Accessibility (low cost)	• Difficult three-dimensional interpretation of the anatomy • High variability (during the procedure) • Similar echogenicity between chronic edema and tumor mass
3D-US	• Volumetric image (avoid arbitrary planes) • Different ways of image production (asynchronous, mechanical translation, and phased array) • Flexible field of view	• Pressure applied to the brain produce artifacts • Slow acquisition of image reconstruction (phases array is comparable to that of 2D-US) • Reconstruction quality (subject to interoperator variability and highly sensitive to motion artifacts)
HF-US	• Frequency up to 25 MHz (higher resolution) • More reliable demarcation of tumor margins • Better differentiation of peritumoral edema • Small transducers (easier insertion in cavities)	• Poor depth (penetration) of view • Visualization of small regions at a time (lower intraoperative usefulness)
D-US	• Assess tumor vascularity • Different modalities (color, power and 3D) • Power D-US: less noise, less angle-dependent, higher resolution of small vessels, and no aliasing. • 3D D-US: simultaneously demonstrate arteries and veins (include small-caliber vessels).	• Poor resolution and high noise • D-US: angle-dependent (flow perpendicular to US waves = no signal) • Power D-US: less information about flow direction and velocity, vessels appear larger (visualization of small vessels of limited relevance) • Aliasing (artifact): incorrect flow magnitude
US-E	• Maps elastic properties of tissue	• Negligible acquisition and computation times • Uncertain correlation with histopathology • Brain tissue damage during assessment • High noise
CE-US	• Real-time visualization of tissue vascularity (identified tumors that recruit an avid vascular supply) • Help the surgeon to navigate around vascular structures • Image quality is unaffected by angle of insonation • Unlike D-US, CE-US can simultaneously show high- and low-flow vessels (perfusion dynamics)	• Require that image occur prior to coagulation of tumor feeding vessels (alter operative workflow) • Field of view is constant during contrast injection • No FDA-approved contrast agents for neurosurgery

2D-US: two-dimensional ultrasound; 3D-US: three-dimensional ultrasound; HF-US: high-frequency ultrasound; D-US: Doppler ultrasound; CE-US: contrast-enhanced ultrasound; US-E: ultrasound elastography; and FDA: Food and Drug Administration.

Table 1.
Comparison of the advantages and limitations between the different ultrasound (US) modalities.

glioblastomas, and metastasis. A very remarkable aspect regarding the usefulness of 3D-US is that the use of iUS to delineate the histopathological margin of the tumor has been shown to be equivalent to MRI [30]. A series of glioma resections performed by Sure et al. with the integration of US technology into neuronavigation to define the main vascular structures in preoperative images, highlight the limitations to identify these structures due to brain-shift in the use of neuronavigation [31]. On the other hand, they highlight the usefulness of the D-US to locate and guide the surgical approach considering the vasculature of the tumor and the adjacent vascular structures. Other methods such as power Doppler and CE-US have allowed intraoperative navigation around major vascular structures without relying on preoperative imaging that does not account for brain displacement [32, 33]. However, it must be considered that the magnitude of CE-US does not correlate with the degree of contrast enhancement observed on CT or MRI [34]. The utility of E-US is still in the early stages of characterization with respect to brain tumor resection. As mentioned earlier, this study is based on the use of pulsations to identify the tension/rigidity of a tissue in order to differentiate the tumor from the normal parenchyma. However, these images have not been with MRI or histopathology, so their true utility is unknown. On the other hand, it has been shown to be useful in predicting the location of dissection planes during resection. Scholz et al. evaluated brain tumors of different etiologies, showing that the E-US allows to differentiate the tumor from the normal parenchyma. Therefore, it could be said that this modality is especially useful to define the resection margin [16].

2.5.1 Assessment of extent of resection

The extent of the resection contributes to improving patient survival in the surgical management of brain tumors [35]. However, the evaluation of the resection extension is complex, and the use of the US offers a promising option due to its accessibility and real-time feedback. However, its ability to reliably identify residual tumor is limited by a variety of factors [36]. Chacko et al. published an article where brain tissue samples were taken from tumor margins (defined by iUS), showing a correlation between the histopathological study and the iUS greater than 80% [37]. A previous study of intraoperative iUS in glioma resection reported that 89% concordance with histopathology in hyperechoic areas that clearly extended into isoechogenic brain parenchyma, in contrast with a 56% concordance along the hyperechoic rim of the resection cavity [38]. Due to the concern generated by histological confirmation with imaging data, different solutions have been sought, one of them being the use of other modalities other than 2D-US, for example, the use of HF-US that offers superior intraoperative tumor detectability in primary and recurrent surgery for the study of glioblastomas. HF-US was shown to have a higher sensitivity for tumor detection (76%) [12]. On the other hand, comparison of iUS and intraoperative 1.5 T MRI in 26 patients with multiple brain tumors reliably detected residual tumor in those tumors that were larger than 1 cm. However, the usefulness of iUS is limited for smaller tumors [39].

2.5.2 Brain-shift monitoring and compensation

Surgical intervention produces changes in the anatomical arrangement of the brain due to various factors. Due to its low cost (accessibility), security, and speed, the US is a suitable candidate option to compensate for these changes in real time.

These changes can be represented in the form of a deformation field in order to update the preoperative images obtained generally by MRI. The generation of the deformation field is based on an algorithmic alignment of two images of the same anatomy (preoperative and postoperative image). There are different registration strategies for obtaining the deformation field. However, the most used are the rigid and non-rigid techniques, where the rigid maps two images with the translation and rotation of the image, compared to the non-rigid registration where the images can be obtained in a more flexible way. In general, the non-rigid records more accurately represent the observed changes, with the limitation that they require a greater calculation time [40]. Other strategies have been proposed to fuse the iUS with the preoperative anatomical record. However, these studies have been conducted in small groups of patients. These include the use of probabilistic functions that match hyperechoic structures (for rigid use) [41], Bayesian logarithmic registration incorporating local region information to improve compensation for missing tissue [42], the generation of a very similar to US from MRI [43], and D-US recording to preoperative MRI angiography [44]. Mercier et al. described a study that sought to find an intraoperative registration technique that would improve the alignment of US images taken before and after brain tumor resection. The study was performed in 16 cases using 2 different registration methods, the first one was performed with manually selected labels in pre- and post-resection US to calculate the mean distance between corresponding points in the two volumes before and after registration (rigid registration), and in the second one, the surgeon was asked to classify and rate the quality of the alignment before and after registration (nonlinear registration). The mean distance was 2.7 mm after rigid registration, and 1.7 mm after nonlinear registration. Consistent with distance and classification metrics, the nonlinear registration approach significantly improved the alignment of US images [45].

3. Illustrative case

3.1 Case presentation

A 65-year-old female patient began her condition 15 days prior to hospital admission with a throbbing holocranial headache, of variable intensity from 6 to 8 according to the visual analog pain scale, followed by nausea and vomiting, added with dysphasia, and weakness in the left hemibody. During the physical examination, within the important findings, the presence of papilledema (intracranial hypertension) was identified, as well as the finding of left hemiparesia, grade 4/5 and increase in deep tendon reflexes, ruling out the presence of dysphagia and memory loss. It was decided to perform a simple and contrast-enhanced MRI of the brain (**Figure 1**), which evidenced the presence of an intra-axial lesion of the temporo-parietal lobe with heterogeneous enhancement of the periphery. For this reason, it was decided to perform a surgical procedure to remove the tumoral lesion.

3.2 Surgical procedure and outcomes

With the patient under general anesthesia, in dorsal decubitus position and head with lateralization to the left, a Mayfield head frame was placed, fixed with elevation, lateralization to the left, and deflection. Trichotomy, asepsis, and antisepsis (with chlorhexidine) were performed, surgical fields were placed, 2% lidocaine was

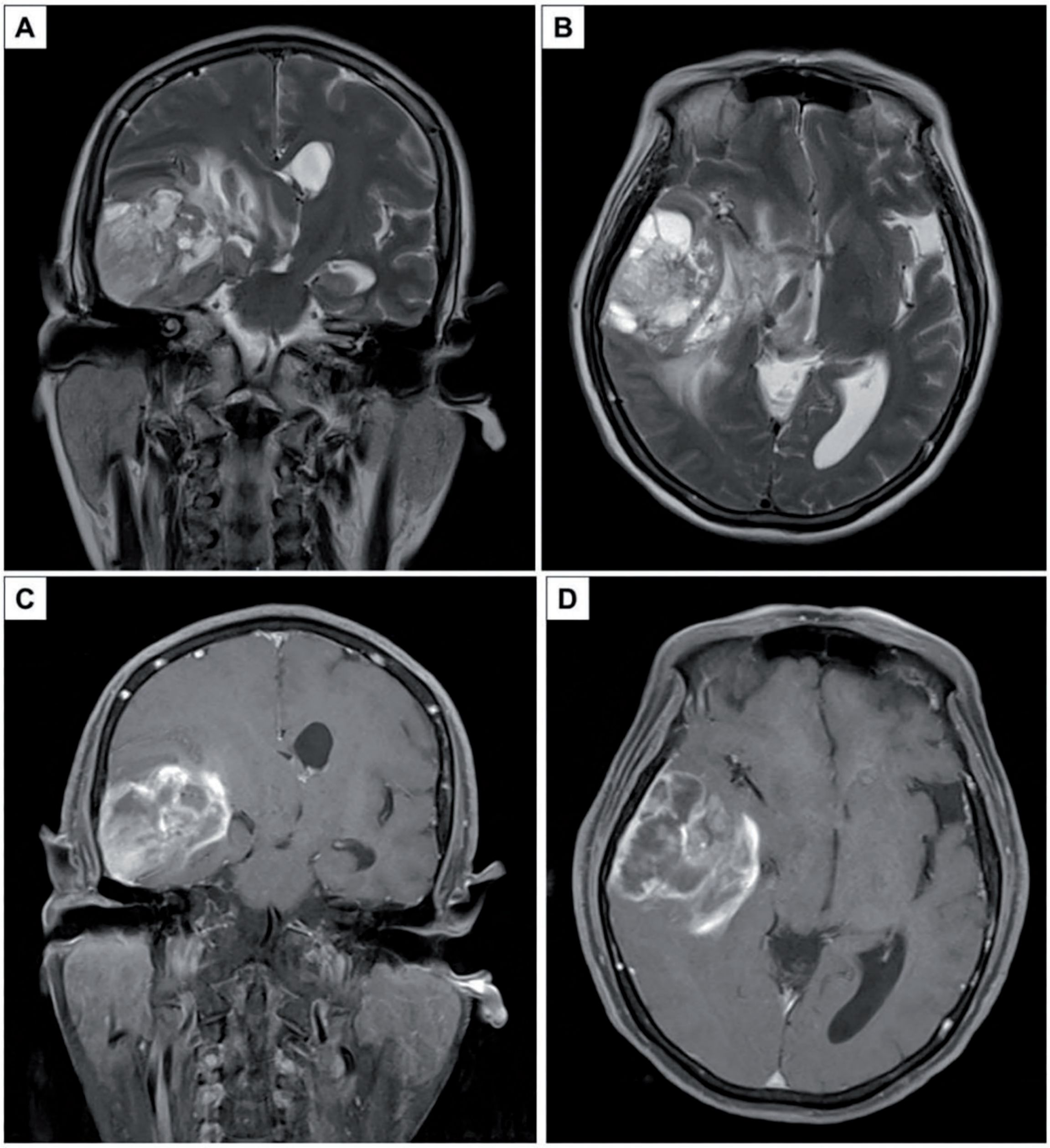

Figure 1.
Preoperative brain magnetic resonance imaging (MRI). T2-weighted MRI (A-B) A. Coronal view. B Axial view. T1. Contrast-enhanced T1-weighted MRI (C-D). C. Coronal view. D. Axial view. The images show a rounded heterogeneous cystic-appearing lesion in the right temporo-parietal region with contrast media uptake, ring enhancement, and peripheral vasogenic edema.

infiltrated, and a right Mark-type incision was made. It was incised with the scalpel in planes up to the pericranium, performing hemostasis with bipolar and preserving muscular structures. Subsequently, a pericranial dissection was performed by dissecting a skin flap and performing an interfacial dissection (displacing the muscle caudally). Afterward, a right fronto-temporal craniotomy was performed, exposing the dura mater to perform a 2D-US scan (Samsung HM70 EVO) (**Figure 2**), identifying the dissection plane from which to start the resection (**Figure 3A–E**), a complete dissection of the tumor mass identified by US in all its limits, as well as the tissue direct visualized with gliosis.

The temporal lobe dissection was performed until the skull base and tentorium were identified. A new US scan was performed to corroborate the complete resection

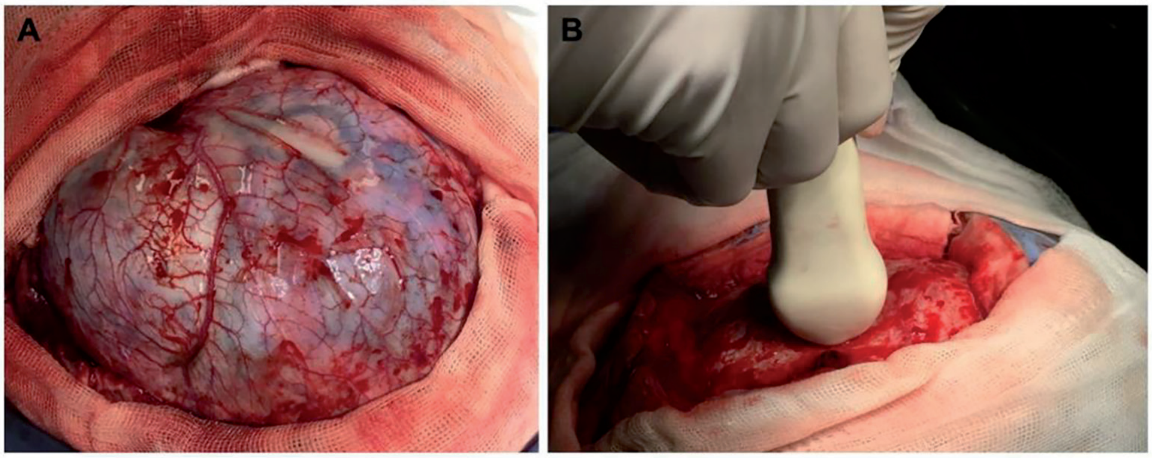

Figure 2.
Surgical approach. A. Fronto-temporal craniotomy. B. Ultrasound scan.

(**Figure 3F**). Subsequently, hemostasis was performed with surgicel and gelfoam, ending the microsurgical time, proceeding to primary closure and plasty of the dura mater with pericranial tissue. Hermetic closure was verified, and bone was placed, then a subgaleal drainage was placed closing the galea, ending by closing the skin with continuous Sarnoff stitches. The patient was discharged from the neurosurgery

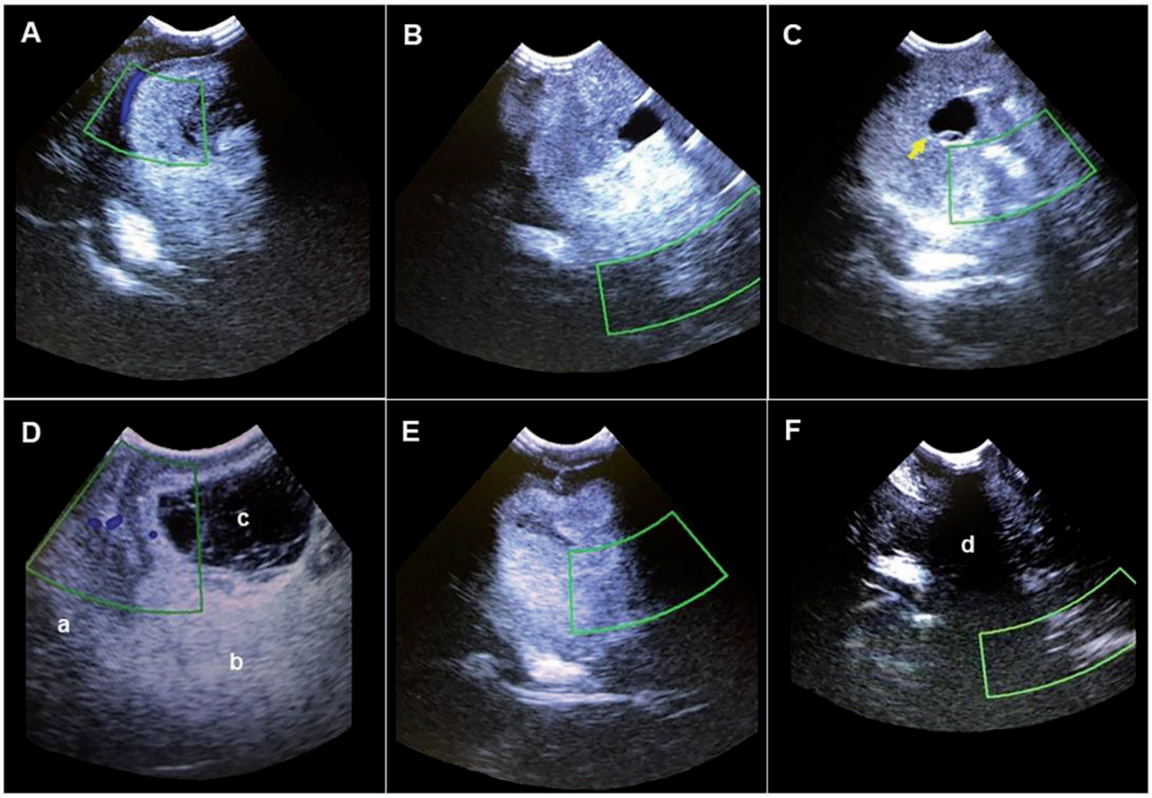

Figure 3.
Intraoperative 2D ultrasound (2D-US). A. One of the advantages of US is to show the perilesional vascular structures as shown in blue in the image. B. The tumoral lesion of the patient of shows a cystic component, also useful to define the characteristics of the tumor. C. The yellow arrow indicates an intratumorally cystic degeneration. D. In this image, it is possible to distinguish the echogenicity of different brain tissues: normal brain tissue (a), tumoral mass (b), and cystic component (c). E. 2D-US allows defining the limits of the tumor lesion, as shown in the differences of echogenicity. F. Secondary navigation after surgical resection allows to evaluate the complete tumor resection, and to avoid resection lodge artifact, it is suggested steering clear of putting hemostatic materials and the surgical field is filled with warm injectable solution to continue iUS mapping (d).

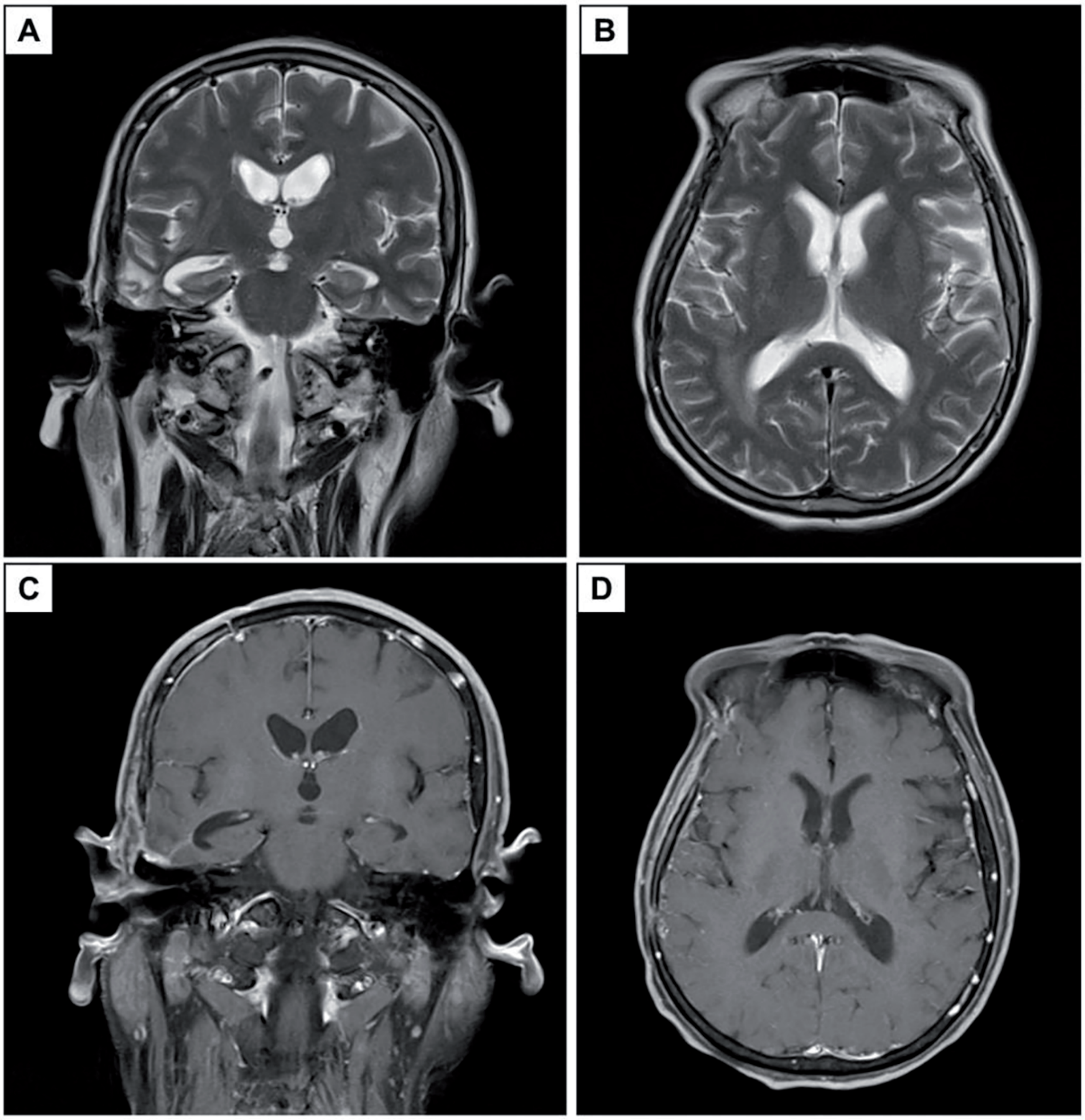

Figure 4.
Postoperative brain magnetic resonance imaging (MRI). T2-weighted MRI (A-B) A. Coronal view. B Axial view. T1. Contrast-enhanced T1-weighted MRI (C-D). C. Coronal view. D. Axial view. The images show a gross total resection of the lesion without recurrence.

service 3 days after the intervention without neurological alterations. MRI studies were obtained at 3, 6, and 10 months, where **Figure 4** shows the last imaging study at 10-month follow-up, showing a gross total resection of the lesion. The histopathological report confirmed the presence of glioblastoma, so it was decided to start adjuvant therapy (Stupp R. protocol) with radiotherapy (fractionated focal irradiation in daily fractions of 2 Gy given 5 days per week for 6 weeks, for a total of 60 Gy) plus continuous daily temozolomide (75 mg per square meter of body surface area per day, 7 days per week from the first to the last day of radiotherapy), followed by six cycles of adjuvant temozolomide (150 mg per square meter for 5 days during each 1 month cycle) [46]. Although recurrence is common in tumors such as glioblastoma, in this case at 10 months of follow-up no recurrence data were observed, due to the large resection of the tumor added to postoperative adjuvant management with chemotherapy and radiotherapy.

3.3 Case discussion

Most first-world countries have adequate technology to achieve complete resections in most of their cases, and it allows them to have better survival rates [47]. However, this requires a very high economic investment in terms of operating room equipment for neurological surgery. In contrast with developing countries, where health systems are limited to federal budgets, it is complicated to have all the tools to ensure maximum resection, so alternative methods to those commonly used (trans-operative MRI, neuronavigation, stereotaxic, or fluorescence through a special filter in the microscope) should be used in developed countries [48]. Our neurosurgery service has continued to use 2D-US as a routine tool in brain tumor surgery, because it is an available and accessible tool (low cost). The fact that it is not cutting-edge technology does not mean that it is less useful, and as the advantages shown in **Table 1**, this imaging tool has a series of modalities that offer great advantages during the evaluation of tumor resection during the intraoperative period.

Among the main disadvantages of the use of 2D-US for the resection of brain tumors is that it requires learning in its use and experience since it requires experience of the neurosurgeon. This means that whoever decides to use this method as a guide for maximum resections must prepare and learn ultrasonography prior to its use in the operating room, either with animal models or simulators. On the other hand, another disadvantage is the inability to plan before the intervention, a very clear advantage of neuronavigation and stereotaxic guided surgery. However, the main advantages of the US are as follows: the correct identification of the lesion after craniotomy and during the procedure (1), the identification of the tumor margins (2), the evaluation of the characteristics of the tumor (3), the evaluation of the vascular structures within the tumor and in its periphery (4), and the compensation phenomena in real time (avoid brain-shift) (5) [3].

In the case presented earlier, as neuronavigation and fluorescence were not available, it was decided to guide the resection with 2D-US, all with the aim of increasing the degree of resection with maximum safety for the patient and achieving adequate survival. As can be seen in the postoperative images, once the craniotomy was performed, an epidural recording of the lesion was started with the transducer (**Figure 2**), the durotomy was planned, and after it, the brain was repeatedly scanned to identify the edges of the lesion (**Figure 3D** and **E**), including some cystic portions and vessels at the periphery of the tumor (**Figure 3A–C**). Throughout the surgical procedure, the extension of the resection was verified with this method, until it was completed (**Figure 3F**), achieving the main objective (maximum resection) (**Figure 4**). Although in some places it is already considered an obsolete method, derived from advances in technology and the implementation of better imaging methods for intraoperative use. According to the literature search, and the results obtained in more than 50 patients (on published data) in which iUS was used for tumor resection including the illustrative case exposes in this book chapter, we consider that this method could be a great alternative due to the advantages mentioned earlier, since it is in real time and does not depend on planning and being very accessible compared to other methods. However, it is necessary to perform well-powered, well-designed, randomized prospective studies that compare the different trans-operative techniques such as MRI, neuronavigation, stereotaxic, fluorescence, and iUS, in terms of survival and cost-effectiveness.

4. Conclusion

During the resection of a brain tumor, efforts are aimed at minimizing the repercussion of the tumor on the neurological integrity of the patient, trying to preserve function with the highest degree of resection possible. Because the US can provide intraoperative (real-time) information, it is useful in guiding surgical resection. The background highlights the reliability of US in the management of tumor pathology, where despite the existence of multiple limitations compared to other methods of tumor resection such as artifacts that occur in the resection cavity and variability, it is necessary to carry out further studies that allow evaluating the efficacy of US in terms of survival, intraoperative tumor identification, and cost-effectiveness, compared with other alternatives.

Conflict of interest

The authors declare no conflict of interest.

Permissions

The permission to use the images/materials included in this study has been obtained.

Acronyms and abbreviations

CSF	Cerebrospinal fluid
CT	computed tomography
CE-US	contrast-enhanced ultrasound
D-US	Doppler ultrasound
HF-US	high-frequency ultrasound
iUS	intraoperative ultrasound
MRI	magnetic resonance imaging
3D-US	three-dimensional ultrasound
2D-US	two-dimensional ultrasound
US	ultrasound
US-E	ultrasound elastogy

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