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Intraoperative ultrasound in brain tumor surgery: A review and
implementation guide. *Neurosurgical Review* **2022**, *45*, 2503–2515.
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Contents

1 One-Sentence Verdict

A comprehensive review of intraoperative ultrasound in brain tumor surgery — covering physics, probe selection, artifact identification, navigation fusion, and advanced techniques (CEUS, elastography) — providing an actionable implementation framework. **Deep read, as domain background for my project.**

2 Research Question & Background Gap

Brain tumor surgery aims for maximal safe resection, requiring real-time intraoperative imaging guidance. Intraoperative MRI (iMRI) is effective but prohibitively expensive and logistically complex for most centers. Intraoperative ultrasound (ioUS) is inexpensive, real-time, and easy to integrate, but has long been perceived as having a steep learning curve, poor

image quality, abundant artifacts, and difficult standardization. This review provides a systematic ioUS implementation guide to lower the adoption barrier and summarizes recent technical advances, particularly CEUS and elastography.

P.S. This is not a research paper proposing new methods but a **review + implementation guide** aimed at clinical practice. The reading focus is extracting domain knowledge relevant to my automatic segmentation project.

3 Core Content

1. 3.1 Ultrasound Physics

Ultrasound uses a piezoelectric transducer to emit 1–20 MHz sound waves. Reflected echoes from tissue acoustic impedance ($Z = \rho c$) differences form B-mode grayscale images. **Higher frequency yields better resolution but shallower penetration** — high-frequency linear array probes suit superficial fine imaging (≤4–5 cm), while low-frequency phased array probes suit deep, wide-field imaging. Tissue echogenicity depends on acoustic impedance gradients: choroid plexus (high gradient) appears hyperechoic, ventricular fluid (low density, homogeneous) appears hypoechoic.

2. 3.2 Probe Selection

Probe Type	Characteristics	Use Case
Phased array	Small footprint, low frequency, wide trapezoidal FOV	Scanning deep structures through small craniotomy
Linear array	High frequency, high resolution, shallow penetration	Intracavitary scanning for residual tumor
Micro-curved	Mid-frequency, balanced FOV and resolution	General-purpose, balancing coverage and clarity

Linear array probe sensitivity for residual tumor detection (79%) approaches iMRI (83%) and far exceeds conventional phased array (21%) [8]. The authors recommend a dual-probe strategy: micro-curved for global survey + linear array for intracavitary fine inspection.

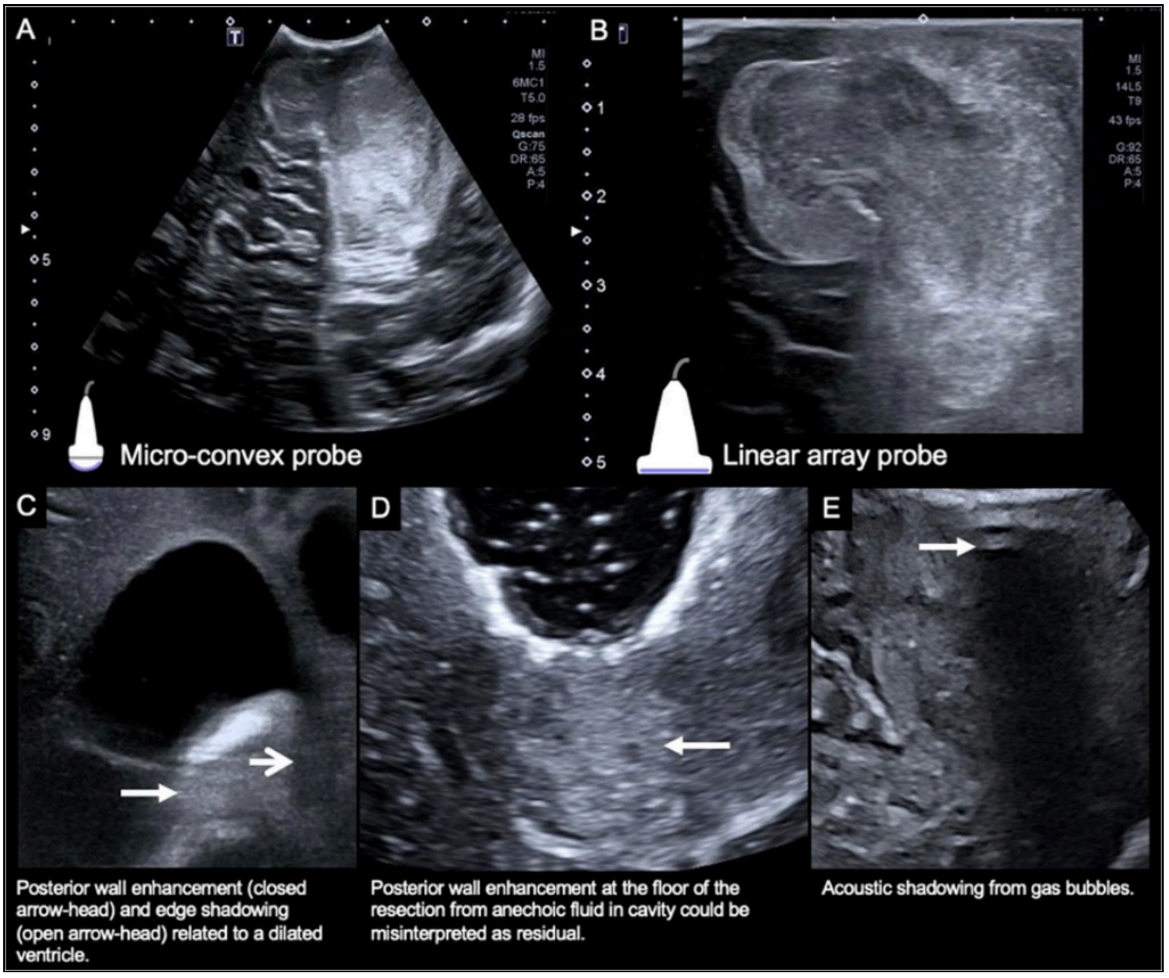

Figure 2: Micro-curved vs linear array image comparison, and common artifact examples (posterior wall enhancement, edge shadowing, bubble acoustic shadow)

3. 3.3 Artifact Identification & Management

Artifacts are among the biggest practical obstacles in ioUS, potentially causing missed residual tumor or excessive resection of normal brain tissue.

Artifact	Cause	Appearance	Mitigation
Acoustic shadowing (AS)	Complete reflection/absorption at high-gradient interfaces	Dark zone posterior to interface	Adjust probe angle, avoid bubbles
Posterior acoustic enhancement (PAE)	Weak attenuation in fluid, enhanced deep echoes	False hyperechogenicity at resection cavity floor	Reposition probe, use intracavitary probe, compare with prior scans
Ring-down artifact	Fluid resonance between bubbles	Trapezoidal "staircase" shadow	Surgicel is a common source; watch hemostatic materials
Edge shadowing	Diffraction at anechoic structure margins	Vertical dark lines beside ventricle walls	Normal phenomenon, identify and ignore

Warning Blood clots, contusion, and edema also alter the surgical field appearance — clots and contusion appear hyperechoic, easily confused with residual tumor. Irregularly protruding hyperechoic foci are histologically proven tumor in 89% of cases, while uniform hyperechoic rims along the resection cavity wall contain tumor in only 56% [15].

4. 3.4 Navigated Ultrasound & US-MRI Fusion

Navigated 2D US (n2DUS): Real-time 2D ultrasound overlaid on navigated MRI/CT, improving orientation and tumor boundary identification. Limitations: single plane, probe occupies surgical field.

Navigated 3D US (n3DUS): After acquiring a 3D volume, retrospective multiplanar reconstruction is possible, the probe can be removed, and comparison with prior scans is facilitated. Sensitivity for residual tumor detection is 71%, comparable to MRI navigation [24,25].

Brain shift: As surgery progresses, US-MRI fusion accuracy degrades (shift up to 15 mm [27]). Rigid registration can only partially compensate for unidirectional displacement; non-rigid registration methods are still under research and cannot yet correct in real time. Experienced teams therefore tend to: **use US-MRI fusion for overall orientation, and real-time US alone for judging residual** [32].

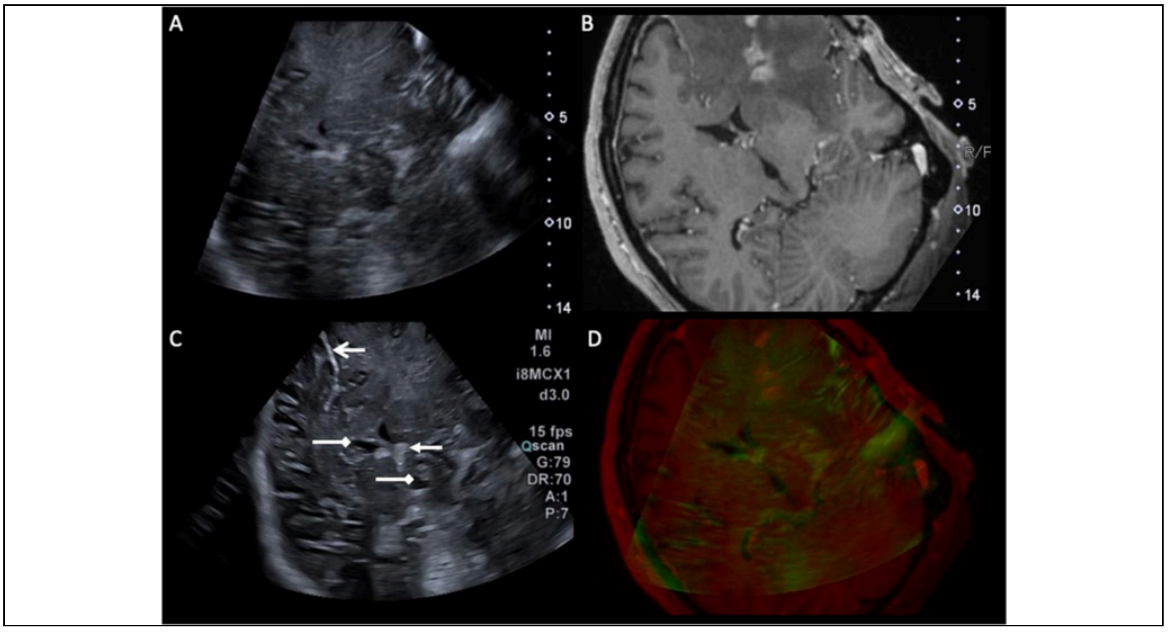

Figure 3: Navigated 3D US with MRI fusion example, and anatomical landmarks for orientation (falx cerebri, ventricles, choroid plexus)

P.S. Brain shift is the fundamental cause of registration accuracy degradation and the core challenge for MRI→iUS registration in my project.

5. 3.5 Tumor Ultrasound Appearance

Tumor echogenicity depends on cellular density. Solid portions of intracranial tumors are typically moderately hyperechoic, with **high-grade gliomas (HGG) and metastases slightly more echogenic and heterogeneous than low-grade gliomas (LGG)** (necrotic areas hypo/isoechoic, cystic areas very hypoechoic, hemorrhage variable).

Tumor boundary visibility depends on echo contrast + infiltration extent. Primary GBM has

clear boundaries, while diffuse LGG and recurrent GBM (post surgery + chemoradiation) have blurred boundaries.

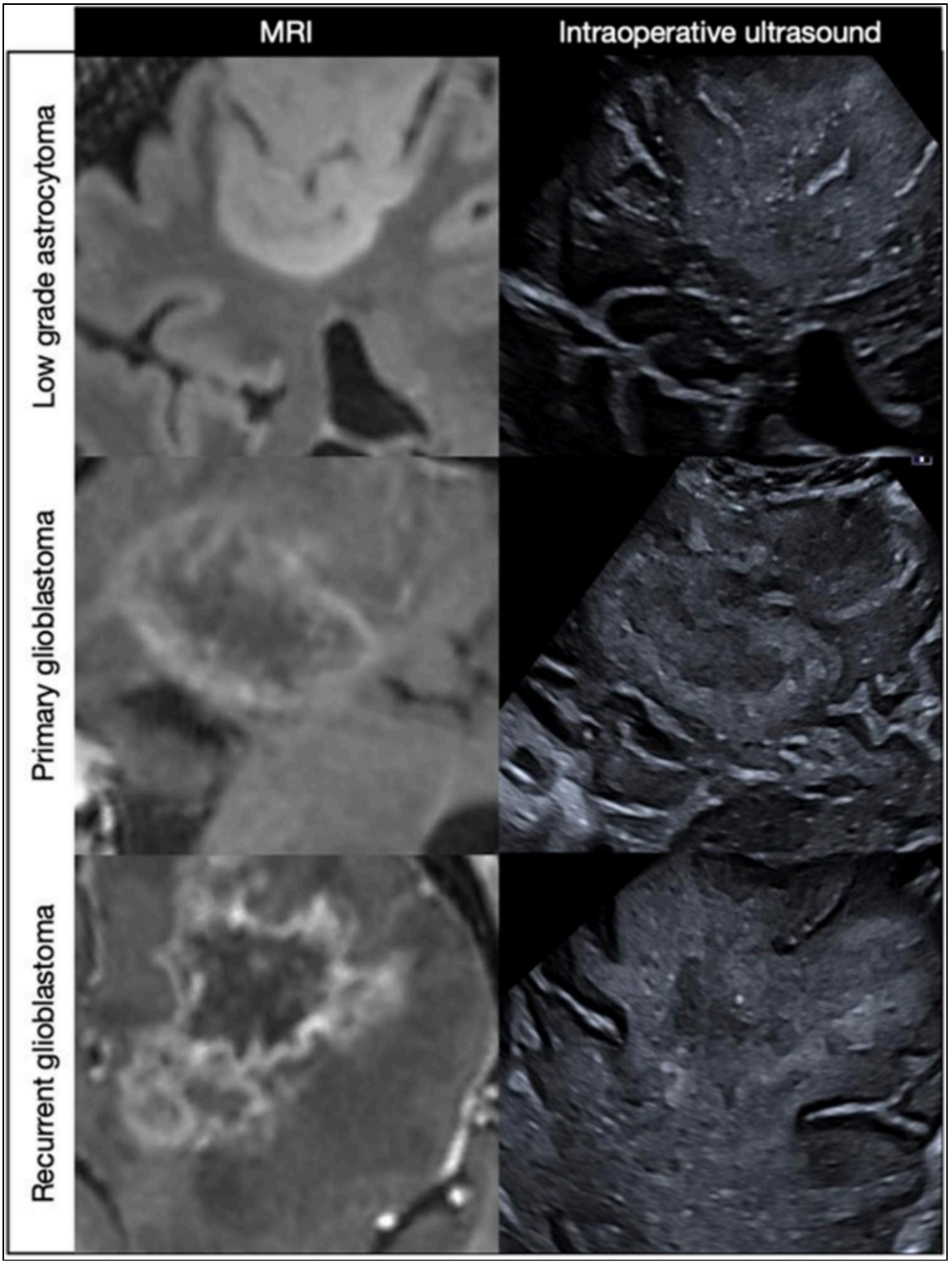

Figure 4: Three tumor types – MRI vs US comparison. Primary GBM has clear boundaries, LGG is fair, recurrent GBM is nearly invisible on US

Figure 4 directly illustrates the difficulty gradient for automatic segmentation: primary GBM > LGG > recurrent GBM. If training data is dominated by primary tumors, model generalization to recurrent/diffuse tumors needs special attention. As a review, the figures serve illustrative rather than evidentiary purposes, with no over-interpretation observed.

6. 3.6 Advanced Techniques

Contrast-enhanced ultrasound (CEUS): Microbubble contrast agent injection (blood-pool type) enhances tumor visualization and boundary definition. HGG contrast-enhanced regions show high concordance with MRI gadolinium-enhanced T1w [39]. Recommended protocol: baseline CEUS after craniotomy before dural opening, repeat after resection to check for residual. CEUS sensitivity for residual detection exceeds conventional B-mode [41,45,46] and works better combined with 5-ALA.

Elastography: Assesses tissue stiffness differences. LGG is typically stiffer than surrounding brain, HGG typically softer [50]. Still in research phase; clinical translation is limited by operator dependence and interpretation difficulty.

4 Critical Assessment

7. 4.1 What the Paper Explicitly States

- ioUS technology has significantly advanced, with major improvements in image quality and navigation tools
- Linear array probe sensitivity for residual detection (79%) approaches iMRI (83%)
- CEUS enhances tumor visualization and residual detection
- Brain shift degrades US-MRI fusion accuracy; non-rigid registration is not yet mature
- Standardized scanning protocols and dual-probe strategy recommended

8. 4.2 What Can Be Reasonably Inferred

Ultrasound image quality varies enormously (operator, probe, settings, craniotomy size), meaning training data distributions will be wide and generalization is the core challenge.

Artifacts and surgical changes are the primary segmentation confounders: posterior wall enhancement, blood clots, and edema can all be misclassified as tumor by models. If training data lacks these confounders, models will perform poorly in real surgical scenarios.

Ultrasound visibility varies greatly across tumor types (Figure 4), making it unlikely that a single model performs well on all types. The tumor-type distribution in datasets deserves attention.

9. 4.3 What Remains Uncertain

The review cites data from different centers, equipment, and operators — specific numbers (e.g., 79% sensitivity) have limited generalizability. What impact do CEUS and elastography have on automatic segmentation model training? The review targets human operators, but these advanced modalities could also provide additional features for DL models. How much does non-rigid registration actually improve accuracy? The review says "promising but immature" without quantitative comparisons.

10. 4.4 Confirmation Bias Self-Check

This review reinforces the narrative that "ioUS is useful and improving." As someone working on an ultrasound-related project, I may accept this too readily without sufficient criticism. The cited studies generally have small sample sizes from specific centers, and extrapolating specific numbers (e.g., linear array sensitivity 79%) as universal conclusions is unwarranted.

5 Relevance to My Project

This review provides the **domain background knowledge** needed for my project, helping me understand ultrasound image physics, artifact sources, and the clinical challenges facing automatic segmentation.

Key takeaways directly guiding my work: registration accuracy degrades as surgery progresses (brain shift), and my pipeline uses pre-resection ultrasound for registration — the best time point for accuracy. If extended to mid/post-resection in the future, the registration approach would need redesigning. Small tumor difficulty is not just a deep learning problem but an inherent limitation of human expertise and ultrasound physics, providing clinical context for the low small-tumor Dice scores in Faanes 2025. Data quality is highly operator- and probe-dependent — ReMIND includes multiple probe types and acquisition conditions, potentially requiring data normalization or domain adaptation during training. Posterior acoustic enhancement and blood clots are major false-positive sources, so Precision metrics deserve special attention beyond Dice.

Retrospective connections after engineering practice (added 2026-03-23): The actual failure modes encountered in Route A registration can be explained using this review's clinical knowledge. MI registration failed on ~13% of patients (8/61 passing all automatic metrics but visually incorrect). The posterior wall enhancement and edge shadowing described in §3.3 produce hyper/hypoechoic regions in iUS resembling tumors. MI metrics cannot distinguish "tissue acoustic impedance interfaces" from "artifacts" and may align MRI to artifact regions rather than true anatomical correspondences — consistent with MI's purely statistical nature (it optimizes grayscale distribution correlation, not anatomical understanding).

The higher post-dura exclusion rate is explained by brain shift beginning immediately after dural opening (up to 15mm), causing post-dura iUS anatomy to deviate from pre-operative MRI. Rigid registration cannot compensate for non-rigid deformation, explaining why some cases pass at pre-dura but fail at post-dura. Extreme pseudo-label volumes (ReMIND-058 reaching 14.5M voxels) can be explained by large tumors presenting diffuse heterogeneous echogenicity in iUS with unclear boundaries — when MRI annotations cover a large region and registration is slightly off, the entire FOV may be covered by pseudo labels.

Probe type impact on data quality is worth investigating. ReMIND metadata (probe model, frequency) has not been systematically checked. The review's linear vs phased array sensitivity difference (79% vs 21%) means mixed-probe datasets may exhibit substantial inter-case image quality variation, affecting registration and segmentation consistency.

Not immediately relevant but worth noting: CEUS and elastography are not in my pipeline (ReMIND only has B-mode), but if multi-modal ultrasound data becomes available in the future, these techniques could provide additional segmentation cues. The review mentions "irregularly protruding hyperechoic foci are tumor 89% of the time" — could such

morphological features serve as model priors, e.g., adding shape constraints in post-processing?

6 Key References

- **Coburger et al. [8]**: Linear vs phased array vs iMRI sensitivity comparison — demonstrates linear probe value
- **Selbekk et al. [10]**: Systematic summary of ultrasound artifact minimization methods
- **Nimsky et al. [27]**: Brain shift quantification (up to 15 mm) — physical limit of registration accuracy
- **Reinertsen et al. [31]**: Brain shift correction methods — prior work by Faanes 2025 co-author Reinertsen
- **Prada et al. [39,41,44]**: CEUS in brain tumor surgery series

#review #background-knowledge #ultrasound #MRI #B-mode #CEUS #elastography #US-MRI-fusion #navigated-ultrasound #high-priority