Research Article

Intraoperative Ultrasound For Identification Of Vascular Structures During Intracranial Tumour Resection And Minimisation Of Intraoperative Haemorrhagic Complications: A Narrative Review

Usarov Muhriddin Shuhratovich

Doctoral Candidate, Department of Medical Radiology, Faculty of Postgraduate Education, Samarkand State Medical University E-mail: usarovmuxriddin0777@gmail.com
ORCID ID: https://orcid.org/0009-0000-9733-1866

Abstract

Background. Injury to arteries, perforators and draining veins is among the most consequential events in intracranial tumour surgery, and the resulting haemorrhage or infarction accounts for a substantial share of new postoperative deficits. Intraoperative ultrasound (ioUS) is the only widely available imaging modality that depicts both tumour and flowing blood in real time, at the operative site, without ionising radiation and without a major interruption of workflow.
Objective. To review how the individual ioUS modalities — B-mode, Doppler and power Doppler, contrast-enhanced ultrasound (CEUS) and navigated three-dimensional acquisition — contribute to the identification of vascular structures during tumour resection, and to examine critically what the published evidence does and does not establish about the effect of ioUS on intraoperative haemorrhagic complications.
Findings. ioUS reliably demonstrates flowing vessels down to the calibre of the lenticulostriate perforators, and navigated three-dimensional power Doppler allows their displacement to be re-assessed as the brain shifts during resection. CEUS adds a temporally resolved arterial and venous phase and improves delineation of perfused tumour. Pooled diagnostic accuracy for residual tumour is moderate: sensitivity 72.2% and specificity 93.5% in one meta-analysis of 409 diffuse gliomas, and sensitivity 75% (95% CI 62–84) with specificity 88% (95% CI 79–94) in another of 542 patients, with consistently better performance in low-grade than in high-grade lesions. For extent of resection the evidence is stronger: a randomised trial reported complete resection in 8 of 23 (35%) ultrasound-guided glioblastoma operations versus 2 of 24 (8%) with standard neuronavigation ($p = 0.036$), and a meta-analysis of 732 patients found a risk ratio for gross total resection of 2.02 (95% CI 1.31–3.10) in favour of ioUS. By contrast, no controlled study has been designed to test whether ioUS reduces intraoperative haemorrhage. The available complication data are uncontrolled: a single-arm meta-analysis reports a pooled complication rate of 15% (95% CI 7–23) without a comparator, and the randomised trial found no difference in complication rates between arms.
Conclusions. The rationale for using ioUS to identify and preserve vessels is anatomically sound and supported by technical series, and the benefit for extent of resection is now supported by randomised and pooled data. The specific claim that ioUS lowers the rate of intraoperative haemorrhage remains, however, unproven; it is a plausible mechanism that has not been the primary endpoint of any adequately powered study. Trials reporting vascular injury and intraoperative bleeding as prespecified outcomes are needed.

Keywords: intraoperative ultrasound; brain tumour; vascular identification; power Doppler; contrast-enhanced ultrasound; intraoperative haemorrhage; brain shift; neuronavigation.

1. Introduction

Intraoperative ultrasound entered neurosurgical practice at the beginning of the 1980s, when Rubin and colleagues described the sonographic examination of the brain through an open craniotomy and, shortly afterwards, the localisation and characterisation of intracranial masses [1,2]. Enthusiasm was followed by four decades of uneven adoption. The reasons are well documented: the image quality of early systems was poor, the oblique two-dimensional planes were unfamiliar to surgeons trained to read orthogonal computed tomography and magnetic resonance images, large lesions exceeded the field of view of the available probes, and the bottom of the resection cavity was frequently obscured by artefact [10].

Most of these objections have been addressed by modern equipment, and the modality has re-entered mainstream practice for a reason that no static preoperative dataset can satisfy. Neuronavigation based on preoperative magnetic resonance imaging becomes progressively unreliable as the brain shifts under the influence of cerebrospinal fluid loss, gravity and the removal of tumour mass [4,5]. Every structure the surgeon wishes to avoid

moves, and vessels move with the parenchyma that carries them. An imaging modality that can be repeated as often as required, at the operative site, without moving the patient, addresses this problem in a way that intraoperative magnetic resonance imaging, whose benefit for extent of resection was established in a randomised trial [36], achieves only at far greater cost and with a substantial interruption of the procedure. The applications of ultrasound in tumour resection — navigation, assessment of extent of resection, and brain shift compensation — have been reviewed in detail elsewhere [12,39].

The literature on ioUS has concentrated overwhelmingly on one question: does it increase the extent of resection? That question now has reasonably good answers. A second question has received much less systematic attention, although it arguably matters more to the individual patient sitting in the operating room: does real-time visualisation of flowing blood help the surgeon avoid injuring vessels, and does it reduce intraoperative haemorrhage? This review addresses the second question directly. It sets out the physical basis on which each ultrasound modality depicts vessels, describes what can and cannot be seen in practice, examines the specific problem of vascular displacement during resection, and then assesses — sceptically — the strength of the evidence linking ioUS to haemorrhagic outcomes.

2. Technical Basis Of Vascular Imaging With Intraoperative Ultrasound

2.1 B-mode

Grey-scale B-mode remains the foundation of intraoperative sonography and is the modality in routine use in the large majority of reported series. The step change in its acceptability came with the improvement in image quality documented by Unsgaard and colleagues at the beginning of the 2000s, which made real-time two-dimensional guidance a practical proposition rather than a research technique [6]. Vessels of sufficient calibre appear as anechoic tubular or round structures depending on the plane of section, and pulsation is visible in real time. Image quality depends heavily on transducer frequency, and the trade-off is unavoidable: higher frequencies improve spatial resolution but are attenuated more rapidly by scattering and absorption, so deep structures are poorly resolved [10]. Unsgård and colleagues recommend matching probe to depth — a 5 MHz (4–8 MHz) probe gives optimal image quality between approximately 2.5 and 6 cm from the probe tip, whereas a 12 MHz linear probe is preferable for superficial lesions and gives its best image from the first few millimetres down to about 4 cm [8,10].

The practical limits of B-mode were quantified by Mair and colleagues, who graded ultrasonographic visibility in 105 ioUS-guided operations on a four-point scale. Only 8% of the 105 lesions were graded as difficult to visualise with no clear border from normal brain, and none were entirely invisible [9]. Visibility, however, is not the same as vascular information: B-mode alone cannot distinguish a patent vessel from a cystic channel or a fluid-filled sulcus, and this is precisely the distinction on which vascular safety depends.

2.2 Doppler and power Doppler

Doppler interrogation resolves that ambiguity by detecting motion rather than acoustic impedance. Colour and spectral Doppler give directional and velocity information but are angle-dependent, which is a genuine constraint in a resection cavity where the probe cannot always be positioned favourably. Power Doppler encodes the integrated amplitude of the Doppler signal rather than its frequency shift, which makes it substantially more sensitive to slow flow and largely independent of insonation angle, at the cost of losing directional information [32].

For the identification of small perforating arteries this sensitivity is decisive. Šteňo and colleagues used navigated three-dimensional power Doppler specifically to visualise the lenticulostriate arteries during resection of insular grade II gliomas in six consecutive patients [13]. The clinical problem they addressed is a paradigm case for this review: the lenticulostriate arteries usually lie just behind the medial tumour border but may be encased by tumour, and their intraoperative injury typically produces dense hemiplegia. Their technique permitted near real-time imaging of these vessels and, importantly, evaluation of their displacement during the resection itself.

2.3 Contrast-enhanced ultrasound

Intravenous microbubble contrast agents resonate in the ultrasound field and are detected by contrast-specific, low mechanical index sequences. Because microbubbles remain strictly intravascular, CEUS produces what amounts to a real-time angiosonogram, with a distinguishable arterial phase followed by a venous phase [15,17]. Prada and colleagues formalised this application in brain tumour surgery and later demonstrated its use for the dynamic assessment of venous anatomy and function, in which B-mode supplies high-resolution anatomy, Doppler supplies flow, and CEUS supplies the functional and temporal dimension [14,15].

Two properties are relevant to vascular safety. First, the temporal separation of arterial and venous phases allows a vessel adjacent to the tumour to be classified rather than merely detected, which is the information required when deciding whether a vessel is a sacrificial tumour feeder or a transit vessel supplying eloquent territory. Second, CEUS distinguishes perfused tissue from non-perfused material, which is why it improves the identification of residual enhancing tumour after apparent gross total resection [16]. Contrast agents used for this purpose have an established safety profile in non-hepatic applications, and their use is covered by the EFSUMB guidelines [18]; quantitative work has since characterised microbubble distribution in the human brain [19].

2.4 Three-dimensional acquisition and integration with navigation

Freehand two-dimensional scanning demands that the surgeon mentally reconstruct a volume from oblique planes. Navigated three-dimensional systems remove that burden by tracking the probe and reconstructing a volume that can be resliced in the familiar orthogonal planes and fused with preoperative magnetic resonance imaging [7,40]. The clinically important consequence is that a new volume can be acquired at any point in the operation, so the navigation dataset can be refreshed rather than merely corrected. Applied to Doppler data, the same principle yields a three-dimensional angiographic volume in which the current position of a vessel, not its preoperative position, is displayed.

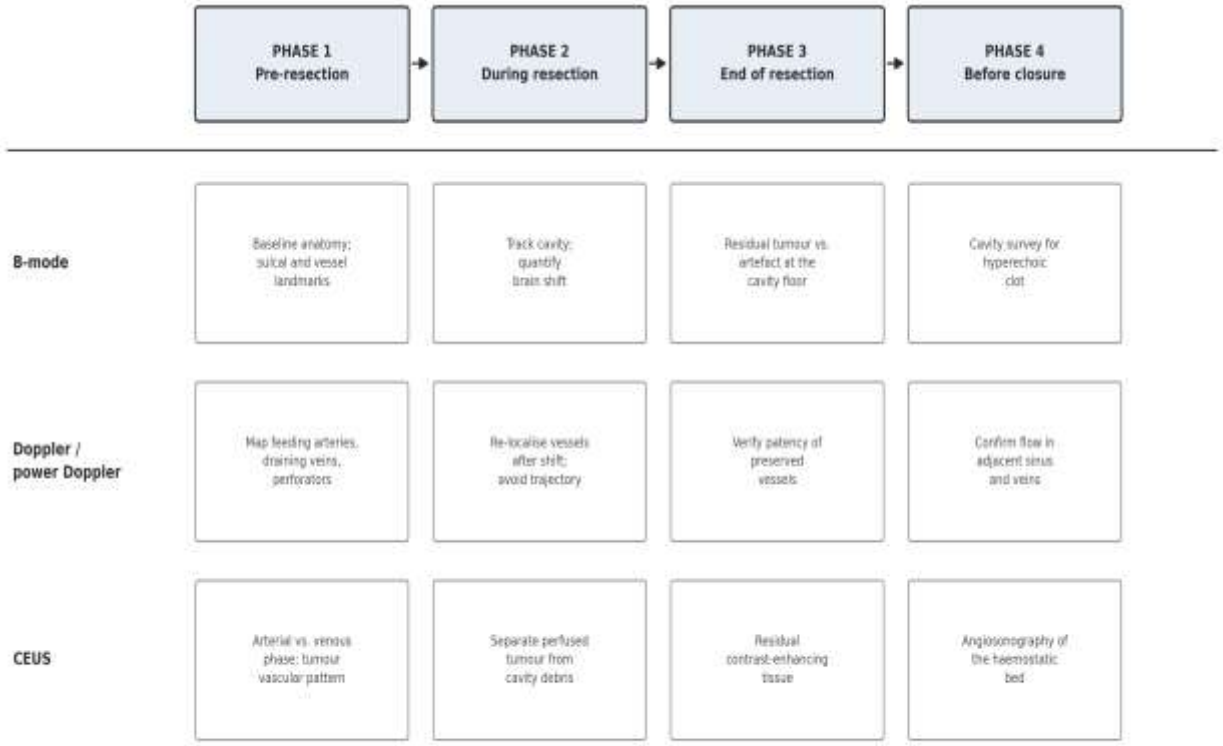

Figure 1. Contribution of each intraoperative ultrasound modality across the four phases of a tumour resection. The columns correspond to the points at which imaging is repeated; the rows show what each modality adds at that point. The scheme emphasises that vascular information is not acquired once but is refreshed as the anatomy changes. Original figure prepared by the authors.

3. Identification Of Vascular Structures During Resection

3.1 Arteries and perforating vessels

Large arteries are rarely the problem. The vessels that cause avoidable catastrophe are small, deep and easily mistaken for tumour: lenticulostriate perforators in insular surgery, thalamoperforators around deep-seated lesions, and the transit vessels that traverse a tumour without supplying it. Power Doppler, especially when acquired as a

navigated three-dimensional volume, addresses exactly this category [13]. The pre-resection acquisition establishes which vessels lie within the planned corridor; repeated acquisition during resection establishes where those vessels have moved to.

A distinction that matters operatively, and which multiparametric ultrasound supports, is that between tumour-feeding arteries — which may be coagulated to devascularise the lesion — and vessels of passage, whose sacrifice produces infarction in territory remote from the tumour. Neither B-mode nor Doppler alone resolves this reliably; the combination of vessel course on three-dimensional Doppler with contrast timing on CEUS is more informative than either [11,14].

3.2 Veins and dural sinuses

Venous injury is under-appreciated relative to arterial injury, but venous infarction after sacrifice of a dominant draining vein or occlusion of a sinus is a well-recognised cause of postoperative deterioration, and the resulting oedema and haemorrhagic transformation may not become apparent until after closure. Veins are slow-flow, thin-walled and collapse under probe pressure, which makes them harder to demonstrate than arteries on conventional Doppler. Prada and colleagues addressed this specifically, showing that multimodal ultrasound — B-mode for anatomy, Doppler for flow, CEUS for functional angiosonography — permits dynamic characterisation of venous compartments in real time, including the effect of surgical manipulation on flow [14]. In parasagittal and peritorcular meningiomas, where the surgical decision turns on whether a sinus is patent, occluded or collateralised, this capability has direct operative consequences [27,33,34].

3.3 Tumour vascular architecture by histological type

Vascular patterns differ systematically between tumour types and the imaging strategy should follow. High-grade gliomas are typically hypervascular with disorganised, tortuous vessels and rapid, heterogeneous contrast enhancement; CEUS has been shown to correlate with glioma grade [35]. Low-grade gliomas enhance poorly and their borders are defined more by parenchymal echogenicity than by vascularity, which is one reason ioUS performs better diagnostically in low-grade than in high-grade disease [23]. Meningiomas are extra-axial, usually hypervascular, and characteristically supplied by a dural pedicle whose early identification permits devascularisation before debulking; multimodal ultrasound protocols for meningioma surgery have been described in detail [33,34]. Metastases are frequently well demarcated but may be intrinsically haemorrhagic, and the distinction between tumour and adjacent haematoma on B-mode is not always straightforward [11]. In paediatric neuro-oncology, where the avoidance of repeated ionising radiation carries additional weight, ultrasound-assisted assessment of extent of resection has been evaluated specifically [38].

Table 1. Contribution of each ultrasound modality to intraoperative vascular assessment.

Modality	What it depicts	Principal strength for vascular safety	Principal limitation
B-mode	Acoustic impedance; vessels as anechoic tubular structures	Universally available; establishes anatomical context and cavity landmarks	Cannot distinguish a patent vessel from a fluid-filled channel; artefact at the cavity floor
Colour / spectral Doppler	Frequency shift from moving blood; direction and velocity	Confirms flow and its direction; quantifies velocity	Angle-dependent; insensitive to slow flow in small vessels
Power Doppler	Integrated Doppler signal amplitude	Sensitive to slow flow and largely angle-independent; demonstrates perforators such as the lenticulostriate arteries [13]	No directional information; susceptible to motion artefact
CEUS	Intravascular microbubbles; arterial and venous phases	Temporal separation of arterial and venous supply; distinguishes perfused	Requires intravenous contrast and contrast-specific software; adds procedural steps

Modality	What it depicts	Principal strength for vascular safety	Principal limitation
		tumour from non-perfused material [14–17]	
Navigated 3D acquisition	Volume reconstruction registered to navigation	Volume can be refreshed during surgery, so vessel positions reflect current, not preoperative, anatomy [7,13]	Additional hardware and calibration; acquisition time

Table 2. Transducer selection by target depth, after the recommendations of Unsgård and colleagues [8,10].

Probe	Optimal working range	Comment
12 MHz linear	Surface to approximately 4 cm	Best resolution for superficial lesions and for small vessels close to the cortical surface
5 MHz (4–8 MHz)	Approximately 2.5–6 cm from probe tip	General-purpose intracranial imaging; the usual choice for lesions at intermediate depth
Lower frequency	Beyond approximately 6 cm	Required for deep structures; spatial resolution degrades appreciably, which limits assessment of small perforators

4. Brain Shift And The Moving Vascular Target

The argument for real-time vascular imaging rests on a simple premise: the vessel the surgeon is trying to avoid is not where the preoperative scan says it is. Brain shift begins with dural opening and continues throughout resection, driven by cerebrospinal fluid drainage, gravity, retraction and the progressive removal of mass [4]. Nimsky and colleagues quantified the magnitude of this displacement with intraoperative magnetic resonance imaging and demonstrated that it is large enough to invalidate navigation accuracy [5].

Two consequences follow for vascular safety. First, a vascular map generated before resection has a limited useful life and must be regenerated. Second — and this is a point that favours ultrasound over any preoperative modality — vessels themselves may serve as internal landmarks for the estimation and correction of shift, because they are discrete, echogenic under Doppler, and distributed through the operative field. The technical note of Šteňo and colleagues illustrates the first point concretely: their stated aim was not only to visualise the lenticulostriate arteries but to evaluate their shift during insular tumour resection [13].

It should be acknowledged that ultrasound's own accuracy is not immune to the progress of the operation. Image quality deteriorates as the resection cavity develops, blood and surgical material within the cavity generate artefact, and previously irradiated tissue images poorly [10,26]. The practical implication is that the most reliable vascular map is the one acquired earliest, and that later acquisitions are best interpreted as updates to a known anatomy rather than as independent examinations.

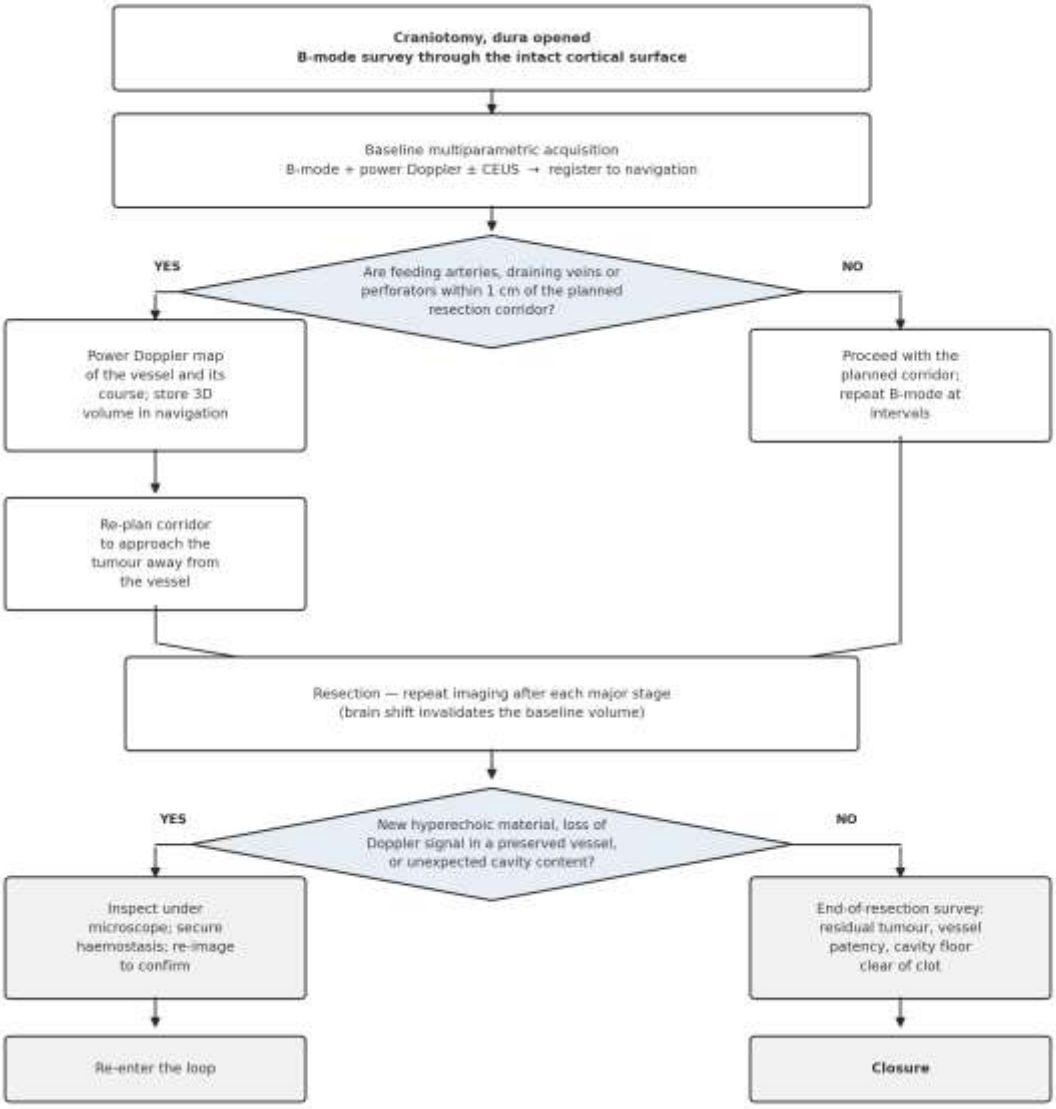

Figure 2. Proposed workflow for the use of intraoperative ultrasound in the identification and preservation of vascular structures. The algorithm is a synthesis of the technical approaches described in references 8, 10, 13 and 14 and is intended as a framework for prospective evaluation; it has not itself been validated in a clinical study. Original figure prepared by the authors.

5. Intraoperative HAEMORRHAGE AND THE ROLE OF ULTRASOUND

5.1 Mechanisms of intraoperative bleeding

Intraoperative haemorrhage in tumour surgery arises through several distinct mechanisms, and the relevant vascular anatomy differs by histological entity as defined in the current World Health Organization classification [3], and ultrasound is relevant to them to very different degrees. Bleeding from the tumour bed in a hypervascular lesion is anticipated and managed by technique rather than by imaging. Inadvertent division or avulsion of an artery of passage, injury to a perforator encased in tumour, and sacrifice or thrombosis of a dominant draining vein are the events in which pre-emptive identification is plausibly decisive. Remote haemorrhage — bleeding at a site distant from the resection, including cerebellar haemorrhage after supratentorial craniotomy — is largely outside the ultrasound field of view and cannot be addressed by this modality at all.

Table 3. Mechanisms of intraoperative bleeding and the plausible contribution of intraoperative ultrasound. The right-hand column states the level of supporting evidence explicitly.

Mechanism	Potential ultrasound contribution	Corresponding finding	Evidence status
Injury to a perforating artery encased by tumour	Pre-resection and repeated power Doppler mapping of the perforator and its displacement	Linear power Doppler signal at the medial tumour border	Technical series only (n = 6) [13]
Division of an artery of passage	Discrimination of feeder from transit vessel using vessel course plus contrast timing	Arterial-phase enhancement without tumour supply	Mechanistic; no comparative study
Sacrifice or thrombosis of a dominant draining vein	Dynamic assessment of venous flow before and after manipulation	Loss or reversal of venous flow signal	Technical note [14]
Sinus injury in parasagittal or peritorcular tumours	Determination of sinus patency and collateral drainage before dural incision	Absent flow in an occluded segment	Descriptive series [27,33,34]
Bleeding from a hypervascular tumour bed	Pre-resection assessment of tumour vascularity to inform strategy	Intense, early contrast enhancement	Correlative studies [35]
Remote haemorrhage	None — outside the field of view	—	Not applicable

5.2 What ultrasound can detect once bleeding has occurred

Acute intracavitary blood is echogenic and can be recognised on B-mode as new hyperechoic material within a cavity that was previously anechoic. In practice, however, this is a less useful signal than it first appears, because blood, haemostatic agents, cottonoid and surgically traumatised parenchyma all generate hyperechoic artefact at the cavity floor — the very artefact that has long been identified as one of the principal limitations of intraoperative ultrasound [10]. The reliable ultrasound contribution after a vascular event is therefore not the detection of the clot but the interrogation of flow: loss of a Doppler signal in a vessel that was patent on the baseline acquisition is specific and actionable in a way that a hyperechoic cavity floor is not.

5.3 A cautionary note on interpretation

It is worth stating plainly what does not follow from the literature. The fact that ultrasound can demonstrate a lenticulostriate artery does not establish that using ultrasound reduces the incidence of lenticulostriate injury; the fact that it can show venous flow does not establish that it prevents venous infarction. These are mechanistic inferences, and they are reasonable ones, but they are not outcome data. The distinction is maintained throughout the following section.

6. The Evidence Base

6.1 Diagnostic accuracy for residual tumour

Two meta-analyses provide the most reliable estimates. Trevisi and colleagues, following PRISMA-DTA and STARD guidance, identified 13 studies (665 diffuse gliomas) and pooled 10 of them (409 gliomas), obtaining a sensitivity of 72.2% and a specificity of 93.5%, with a negative likelihood ratio of 0.29, a positive likelihood ratio of 3 and a diagnostic odds ratio of 9.67; heterogeneity between studies was non-significant, and subgroup analysis demonstrated better performance in low-grade than in high-grade gliomas [23]. Zhang and colleagues pooled 14 studies comprising 542 participants and reported a sensitivity of 0.75 (95% CI 0.62–0.84), a specificity of 0.88 (95% CI 0.79–0.94) and an area under the curve of 0.89, again with better performance in low-grade disease [24]. The two analyses agree on both the magnitude of the estimates and the direction of the subgroup effect, which is reassuring.

Histology-controlled work supports the same picture from a different direction: navigated three-dimensional ultrasound delineates gliomas and metastases with an accuracy that has been compared directly against histopathology [30], and linear array ultrasound in low-grade glioma surgery has been assessed histologically against both conventional ultrasound and intraoperative magnetic resonance imaging [28].

6.2 Extent of resection

Incekara and colleagues conducted the only randomised controlled trial of B-mode ioUS in glioblastoma surgery, enrolling 50 patients between November 2016 and October 2019 at a single centre and randomising them 1:1 to ultrasound-guided resection or resection under standard neuronavigation, with complete contrast-enhancing tumour resection assessed quantitatively by a blinded neuroradiologist. Complete resection was achieved in 8 of 23 (35%) analysable patients in the ultrasound arm and 2 of 24 (8%) in the standard arm (p = 0.036) [20]. Pichardo-Rojas and colleagues subsequently pooled 7 studies (1 randomised trial and 6 retrospective cohorts, 732 patients) and found that ioUS was associated with a higher rate of gross total resection (risk ratio 2.02, 95% CI 1.31–3.10) and higher overall survival (standardised mean difference 0.26, 95% CI 0.12–0.39), although progression-free survival was unaffected [21]. Palavani and colleagues, in a single-arm meta-analysis of ultrasound-guided high-grade glioma resection, reported a pooled gross total resection rate of 64% (95% CI 46–81) and noted that two-dimensional ultrasound accounted for 80% of the imaging used [22]. Earlier single-centre series using navigable three-dimensional ultrasound, with particular attention to malignant gliomas, had pointed in the same direction [29].

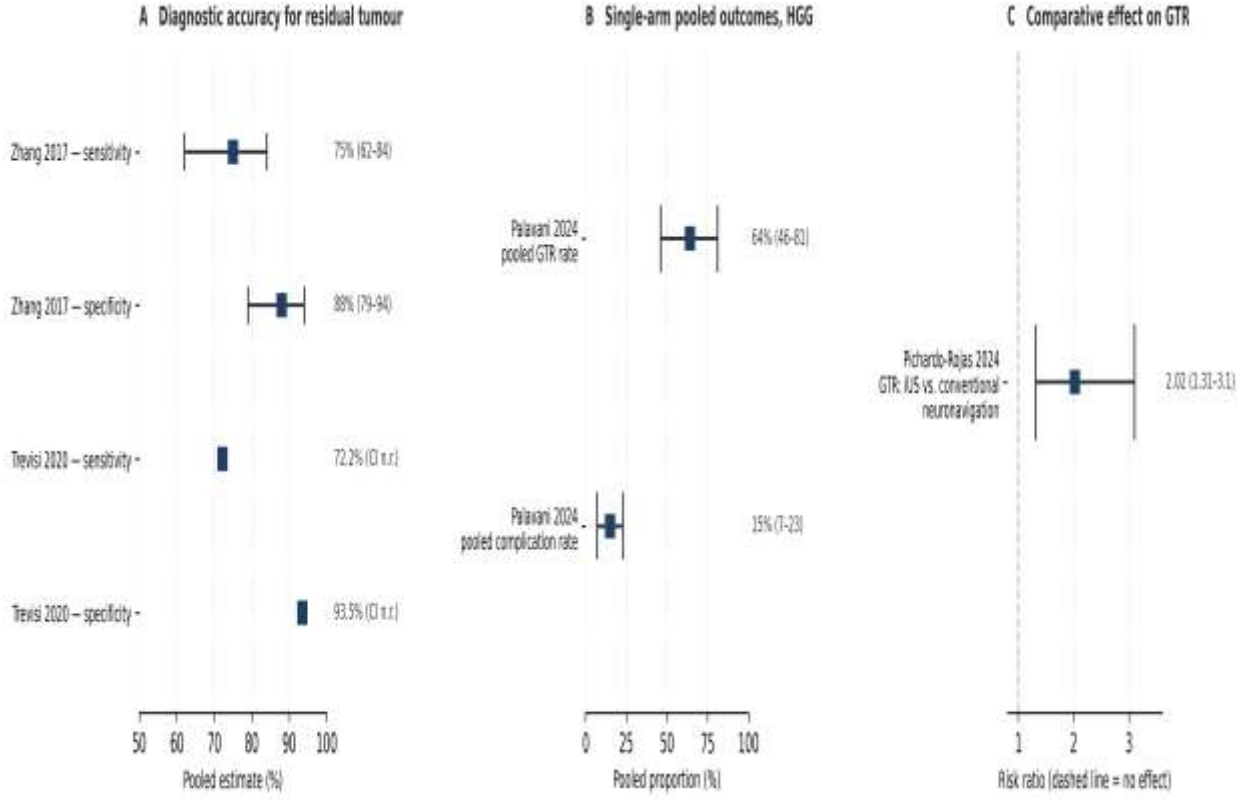

Figure 3. Pooled quantitative evidence for intraoperative ultrasound. (A) Diagnostic accuracy for residual tumour; confidence intervals were not reported for the Trevisi 2020 pooled estimates. (B) Single-arm pooled outcomes in high-grade glioma. (C) Comparative effect on gross total resection; the dashed line indicates no effect. Data from references 21–24. Original figure prepared by the authors.

6.3 Complications and haemorrhage — the gap in the literature

Here the evidence thins markedly. The single-arm meta-analysis of Palavani and colleagues reports a pooled complication rate of 15% (95% CI 7–23) in ultrasound-guided high-grade glioma resection, and the authors themselves note that outcome heterogeneity and limited complication reporting were significant constraints [22]. This figure describes a population; it has no comparator and therefore cannot support any statement about whether

ultrasound raises or lowers complication risk. The randomised trial of Incekara and colleagues did report complication rates and found no difference between the ultrasound and standard arms, alongside no difference in neurological outcome, functional performance, quality of life, overall survival or progression-free survival [20]. That trial, however, was powered for extent of resection, and a trial of 50 patients cannot exclude a clinically meaningful difference in an event as uncommon as significant intraoperative vascular injury.

The Cochrane network meta-analysis of intraoperative imaging technologies for glioma reached a broadly sceptical conclusion about the field as a whole, finding that the certainty of evidence was low to very low, that short- and long-term neurological effects were uncertain, and that network and traditional meta-analyses were in places not possible because of risk of bias, heterogeneity and small trial size [25]. Any claim about haemorrhagic outcomes must be read against that background.

The conclusion that follows is narrow but defensible. Intraoperative ultrasound demonstrably improves extent of resection, and it demonstrably visualises the vessels whose injury causes the most serious intraoperative complications. Whether the second capability translates into a measurable reduction in haemorrhagic events is currently unknown, because no study has been designed to find out.

Table 4. Principal quantitative evidence for intraoperative ultrasound in intracranial tumour surgery.

Study	Design	Population	Principal result	Ref.
Incekara 2021	Randomised controlled trial	50 patients, newly diagnosed glioblastoma	Complete resection 8/23 (35%) with ioUS vs 2/24 (8%) with standard neuronavigation, p = 0.036; no difference in complications, neurological outcome, OS or PFS	[20]
Pichardo-Rojas 2024	Meta-analysis (1 RCT, 6 cohorts)	732 patients, HGG/GBM	GTR risk ratio 2.02 (95% CI 1.31–3.10); overall survival SMD 0.26 (95% CI 0.12–0.39); PFS unaffected	[21]
Palavani 2024	Single-arm meta-analysis	High-grade glioma	Pooled GTR 64% (95% CI 46–81); pooled complication rate 15% (95% CI 7–23), no comparator; 2D ultrasound used in 80%	[22]
Trevisi 2020	Meta-analysis (PRISMA-DTA)	409 diffuse gliomas pooled, from 665 reviewed	Sensitivity 72.2%, specificity 93.5%, LR− 0.29, LR+ 3, DOR 9.67; better performance in low-grade gliomas	[23]
Zhang 2017	Meta-analysis	542 participants, 14 studies	Sensitivity 0.75 (95% CI 0.62–0.84), specificity 0.88 (95% CI 0.79–0.94), AUC 0.89; better in low-grade gliomas	[24]
Fountain 2021	Cochrane network meta-analysis	Glioma, all intraoperative imaging	Low to very low certainty across the field; several planned analyses not possible because of bias and heterogeneity	[25]
Šteňo 2016	Technical note	6 insular grade II gliomas	Navigated 3D power Doppler visualised lenticulostriate arteries and their intraoperative displacement	[13]
Mair 2013	Prospective series	105 ioUS-guided operations	8% of lesions graded difficult to visualise; none invisible	[9]

7. Limitations Of Intraoperative Ultrasound

The limitations of the modality have been catalogued in detail by Šteňo and colleagues and bear directly on vascular applications [10]. Image quality, although greatly improved, remains inferior to magnetic resonance imaging for pre-resectional glioma visualisation and for the detection of small tumour remnants, as the Norwegian group has shown [31]. Acoustic shadowing from bone, air and haemostatic material restricts the field, and the bottom of the resection cavity — where residual tumour and fresh bleeding are most likely to be found — is the region most affected by artefact. Previously irradiated tissue images poorly [26]. Patient positioning that does not permit the cavity to be filled with fluid degrades the examination substantially.

Operator dependence is a genuine and often understated constraint. The interpretation of oblique planes, the recognition of artefact and the optimisation of Doppler settings are learned skills, and their absence limits reproducibility across centres in a way that is difficult to capture in the published literature, which is generated disproportionately by high-volume centres with established ultrasound expertise. This is a plausible source of optimism bias in the pooled estimates presented above.

Finally, the modality is poorly suited to some anatomical situations regardless of operator skill, including comprehensive visualisation of the sellar region during transsphenoidal surgery, for which no optimal probe currently exists [10].

8. Future Directions

Several developments bear specifically on vascular imaging. Contrast-enhanced techniques continue to be refined, and quantitative characterisation of microbubble distribution in the human brain provides a foundation for perfusion measurement rather than qualitative assessment [19]. Elastography adds a mechanical parameter that has been applied to tumour characterisation and to the prediction of meningioma consistency [32,33]. Integration of ultrasound with fluorescence guidance has been described as a combined protocol in high-grade glioma surgery [37].

The more consequential need, however, is methodological rather than technological. If the vascular-safety rationale for intraoperative ultrasound is to be established rather than assumed, studies must report vascular injury and intraoperative haemorrhage as prespecified outcomes, with explicit definitions, adequate sample size and blinded assessment. Registries may be a more realistic vehicle than randomised trials for events of this frequency. Standardised reporting of ultrasound findings would also permit pooling of the kind that is currently prevented by heterogeneity in outcome definition [22,25].

9. Conclusion

Intraoperative ultrasound provides real-time visualisation of both tumour and flowing blood at the operative site, and does so repeatedly, cheaply and without interrupting the procedure. Power Doppler in particular resolves vessels down to the calibre of the lenticulostriate perforators, and navigated three-dimensional acquisition allows their displacement to be tracked as the brain shifts — a capability no preoperative dataset can provide. Contrast-enhanced ultrasound adds temporal discrimination between arterial and venous compartments and improves the identification of perfused residual tumour.

The evidence that ioUS increases the extent of resection is now reasonably strong, resting on a randomised trial and on pooled data from 732 patients. The evidence that it reduces intraoperative haemorrhagic complications does not yet exist in any comparable form. The available complication figure of 15% is uncontrolled, and the only randomised trial to report complications was neither designed nor powered to detect a difference in them. This is a gap in the literature rather than a negative finding, and it is one that the field is well placed to close: the imaging capability is established, the mechanism is plausible, and what remains is to measure the outcome that the mechanism predicts.

References

1. Rubin JM, Mirfakhraee M, Duda EE, Dohrmann GJ, Brown F. Intraoperative ultrasound examination of the brain. Radiology. 1980;137(3):831–832. doi:10.1148/radiology.137.3.6255514

2. Rubin JM, Dohrmann GJ. Intraoperative neurosurgical ultrasound in the localization and characterization of intracranial masses. Radiology. 1983;148:519–524. doi:10.1148/radiology.148.2.6867352

3. Louis DN, Perry A, Wesseling P, et al. The 2021 WHO classification of tumors of the central nervous system: a summary. Neuro Oncol. 2021;23:1231–1251. doi:10.1093/neuonc/noab106
4. Gerard IJ, Kersten-Oertel M, Petrecca K, Sirhan D, Hall JA, Collins DL. Brain shift in neuronavigation of brain tumors: a review. Med Image Anal. 2017;35:403–420. doi:10.1016/j.media.2016.08.007
5. Nimsky C, Ganslandt O, Cerny S, Hastreiter P, Greiner G, Fahlbusch R. Quantification of, visualization of, and compensation for brain shift using intraoperative magnetic resonance imaging. Neurosurgery. 2000;47:1070–1080. doi:10.1097/00006123-200011000-00008
6. Unsgaard G, Gronningsaeter A, Ommedal S, Nagelhus Hernes TA. Brain operations guided by real-time two-dimensional ultrasound: new possibilities as a result of improved image quality. Neurosurgery. 2002;51(2):402–411. doi:10.1227/01.NEU.0000019873.66709.0D
7. Unsgaard G, Rygh OM, Selbekk T, et al. Intra-operative 3D ultrasound in neurosurgery. Acta Neurochir (Wien). 2006;148(3):235–253. doi:10.1007/s00701-005-0688-y
8. Unsgård G, Solheim O, Lindseth F, Selbekk T. Intra-operative imaging with 3D ultrasound in neurosurgery. Acta Neurochir Suppl. 2011;109:181–186. doi:10.1007/978-3-211-99651-5_28
9. Mair R, Heald J, Poeata I, Ivanov M. A practical grading system of ultrasonographic visibility for intracerebral lesions. Acta Neurochir (Wien). 2013;155(12):2293–2298. doi:10.1007/s00701-013-1868-9
10. Šteňo A, Buvala J, Babková V, Kiss A, Toma D, Lysak A. Current limitations of intraoperative ultrasound in brain tumor surgery. Front Oncol. 2021;11:659048. doi:10.3389/fonc.2021.659048
11. Prada F, Ciocca R, Corradino N, et al. Multiparametric intraoperative ultrasound in oncological neurosurgery: a pictorial essay. Front Neurosci. 2022;16:881661. doi:10.3389/fnins.2022.881661
12. Sastry R, Bi WL, Pieper S, Frisken S, Kapur T, Wells W 3rd, et al. Applications of ultrasound in the resection of brain tumors. J Neuroimaging. 2017;27(1):5–15. doi:10.1111/jon.12382
13. Šteňo A, Jezberová M, Hollý V, Timárová G, Šteňo J. Visualization of lenticulostriate arteries during insular low-grade glioma surgeries by navigated 3D ultrasound power Doppler: technical note. J Neurosurg. 2016;125(4):1016–1023. doi:10.3171/2015.10.JNS151907
14. Prada F, Del Bene M, Mauri G, et al. Dynamic assessment of venous anatomy and function in neurosurgery with real-time intraoperative multimodal ultrasound: technical note. Neurosurg Focus. 2018;45(1):E6. doi:10.3171/2018.4.FOCUS18101
15. Prada F, Perin A, Martegani A, et al. Intraoperative contrast-enhanced ultrasound for brain tumor surgery. Neurosurgery. 2014;74:542–552. doi:10.1227/NEU.0000000000000301
16. Prada F, Del Bene M, Fornaro R, et al. Identification of residual tumor with intraoperative contrast-enhanced ultrasound during glioblastoma resection. Neurosurg Focus. 2016;40(3):E7. doi:10.3171/2015.11.FOCUS15573
17. Prada F, Mattei L, Del Bene M, et al. Intraoperative cerebral glioma characterization with contrast enhanced ultrasound. Biomed Res Int. 2014;2014:484261. doi:10.1155/2014/484261
18. Sidhu PS, Cantisani V, Dietrich CF, et al. The EFSUMB guidelines and recommendations for the clinical practice of contrast-enhanced ultrasound (CEUS) in non-hepatic applications: update 2017 (long version). Ultraschall Med. 2018;39:e2–e44. doi:10.1055/a-0586-1107
19. Prada F, Gennari AG, Linville IM, et al. Quantitative analysis of in-vivo microbubble distribution in the human brain. Sci Rep. 2021;11:11797. doi:10.1038/s41598-021-91252-w
20. Incekara F, Smits M, Dirven L, et al. Intraoperative B-mode ultrasound guided surgery and the extent of glioblastoma resection: a randomized controlled trial. Front Oncol. 2021;11:649797. doi:10.3389/fonc.2021.649797
21. Pichardo-Rojas PS, Zarate C, Arguelles-Hernández J, et al. Intraoperative ultrasound for surgical resection of high-grade glioma and glioblastoma: a meta-analysis of 732 patients. Neurosurg Rev. 2024;47:120. doi:10.1007/s10143-024-02354-8
22. Palavani LB, Ferreira MY, Borges PGLB, et al. Ultrasound-guided resection of high-grade gliomas: a single-arm meta-analysis. World Neurosurg. 2024;186:17–26. doi:10.1016/j.wneu.2024.03.033
23. Trevisi G, Barbone P, Treglia G, Mattoli MV, Mangiola A. Reliability of intraoperative ultrasound in detecting tumor residual after brain diffuse glioma surgery: a systematic review and meta-analysis. Neurosurg Rev. 2020;43(5):1221–1233. doi:10.1007/s10143-019-01160-x
24. Zhang G, Li Z, Si D, Shen L. Diagnostic ability of intraoperative ultrasound for identifying tumor residual in glioma surgery operation. Oncotarget. 2017;8(42):73105–73114. doi:10.18632/oncotarget.20394

25. Fountain DM, Bryant A, Barone DG, et al. Intraoperative imaging technology to maximise extent of resection for glioma: a network meta-analysis. Cochrane Database Syst Rev. 2021;(1):CD013630. doi:10.1002/14651858.CD013630.pub2
26. Solheim O, Selbekk T, Jakola AS, Unsgård G. Ultrasound-guided operations in unselected high-grade gliomas — overall results, impact of image quality and patient selection. Acta Neurochir (Wien). 2010;152(11):1873–1886. doi:10.1007/s00701-010-0731-5
27. Solheim O, Selbekk T, Lindseth F, Unsgård G. Navigated resection of giant intracranial meningiomas based on intraoperative 3D ultrasound. Acta Neurochir (Wien). 2009;151(9):1143–1151. doi:10.1007/s00701-009-0395-1
28. Coburger J, Scheuerle A, Thal DR, et al. Linear array ultrasound in low-grade glioma surgery: histology-based assessment of accuracy in comparison to conventional intraoperative ultrasound and intraoperative MRI. Acta Neurochir (Wien). 2015;157(2):195–206. doi:10.1007/s00701-014-2314-3
29. Moiyadi AV, Shetty PM, Mahajan A, Udare A, Sridhar E. Usefulness of three-dimensional navigable intraoperative ultrasound in resection of brain tumors with a special emphasis on malignant gliomas. Acta Neurochir (Wien). 2013;155(12):2217–2225. doi:10.1007/s00701-013-1881-z
30. Unsgaard G, Selbekk T, Brostrup Müller T, et al. Ability of navigated 3D ultrasound to delineate gliomas and metastases — comparison of image interpretations with histopathology. Acta Neurochir (Wien). 2005;147(12):1259–1269. doi:10.1007/s00701-005-0624-1
31. Ravn Munkvold BK, Jakola AS, Reinertsen I, Sagberg LM, Unsgård G, Solheim O. The diagnostic properties of intraoperative ultrasound in glioma surgery and factors associated with gross total tumor resection. World Neurosurg. 2018;115:e129–e136. doi:10.1016/j.wneu.2018.03.208
32. Del Bene M, Perin A, Casali C, et al. Advanced ultrasound imaging in glioma surgery: beyond gray-scale B-mode. Front Oncol. 2018;8:576. doi:10.3389/fonc.2018.00576
33. Prada F, Del Bene M, Moiraghi A, et al. From grey scale B-mode to elastosonography: multimodal ultrasound imaging in meningioma surgery — pictorial essay and literature review. Biomed Res Int. 2015;2015:925729. doi:10.1155/2015/925729
34. Menna G, Olivi A, Della Pepa GM. Integration of different intraoperative ultrasound modalities in meningioma surgery: a 4-step approach. World Neurosurg. 2021;146:376–378. doi:10.1016/j.wneu.2020.12.005
35. Cheng LG, He W, Zhang HX, et al. Intraoperative contrast enhanced ultrasound evaluates the grade of glioma. Biomed Res Int. 2016;2016:2643862. doi:10.1155/2016/2643862
36. Senft C, Bink A, Franz K, Vatter H, Gasser T, Seifert V. Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial. Lancet Oncol. 2011;12(11):997–1003. doi:10.1016/S1470-2045(11)70196-6
37. Della Pepa GM, Sabatino G, La Rocca G. “Enhancing vision” in high grade glioma surgery: a feasible integrated 5-ALA + CEUS protocol to improve radicality. World Neurosurg. 2019;129:401–403. doi:10.1016/j.wneu.2019.06.127
38. Carai A, De Benedictis A, Calloni T, et al. Intraoperative ultrasound-assisted extent of resection assessment in pediatric neurosurgical oncology. Front Oncol. 2021;11:660805. doi:10.3389/fonc.2021.660805
39. Moiyadi AV. Intraoperative ultrasound technology in neuro-oncology practice — current role and future applications. World Neurosurg. 2016;93:81–93. doi:10.1016/j.wneu.2016.05.083
40. Lindseth F, Kaspersen JH, Ommedal S, et al. Multimodal image fusion in ultrasound-based neuronavigation: improving overview and interpretation by integrating preoperative MRI with intraoperative 3D ultrasound. Comput Aided Surg. 2003;8(2):49–69. doi:10.3109/10929080309146040