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Awake Craniotomy in Eloquent-Area Brain Tumors: Indications, Surgical Techniques, and Functional Outcomes

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Abstract
Awake craniotomy has become an important surgical strategy for the management of brain tumors located within or adjacent to eloquent cortical and subcortical regions. The principal objective of the procedure is to achieve maximal safe resection while preserving neurological functions, particularly language and motor abilities. Unlike surgery performed under general anesthesia, awake surgery permits direct assessment of neurological function during tumor resection through real-time cortical and subcortical stimulation mapping. Preoperative functional imaging, neuronavigation, tractography, and careful patient selection complement intraoperative mapping and assist in defining individualized surgical boundaries. Language mapping may incorporate object naming, counting, repetition, reading, writing, and other language tasks, whereas motor mapping can be performed through direct cortical and subcortical stimulation with complementary motor-evoked potential monitoring. Evidence from the selected literature indicates that awake craniotomy can facilitate extensive tumor resection while maintaining acceptable neurological outcomes. Subcortical mapping is particularly important because functional language and motor pathways may extend beyond anatomically recognizable cortical regions. In glioblastoma, available evidence suggests that awake craniotomy can achieve substantial tumor-volume reduction and acceptable gross total resection rates, although the available evidence remains predominantly retrospective. This review discusses the indications, patient selection, preoperative assessment, anesthetic considerations, cortical and subcortical mapping techniques, and functional outcomes associated with awake craniotomy for tumors involving eloquent brain regions.

Keywords: Awake Craniotomy, Eloquent Brain Tumors, Brain Mapping, Language Mapping, Motor Mapping, Maximal Safe Resection

1. Introduction

Brain tumors involving eloquent cortical and subcortical regions present a particular challenge in neurosurgical practice because the tissue requiring removal may be closely associated with functions essential for language, motor control, sensory processing, vision, and other higher neurological processes. Gliomas are frequently infiltrative and may extend into or around functional brain networks, making the distinction between tumor-infiltrated tissue and functionally critical tissue difficult during surgery [1,2]. Consequently, the objective of modern tumor surgery is not simply maximal tumor removal, but **maximal safe resection**, in which the greatest feasible extent of tumor is removed while neurological function and quality of life are preserved [2].

The importance of this balance is particularly evident in eloquent-area tumors. Although greater extent of resection may provide oncological advantages, postoperative neurological deficits can substantially compromise functional independence and quality of life and may reduce the potential benefit associated with aggressive resection [2]. This has led to increasing reliance on functional mapping techniques that permit identification of critical cortical and subcortical structures during surgery.

Awake craniotomy represents one of the most established approaches for functional mapping during resection of tumors in or near eloquent brain regions. The technique allows the patient to remain sufficiently awake and responsive during critical stages of tumor removal so that neurological functions can be directly evaluated while cortical and subcortical structures are electrically stimulated [5]. Its principal advantage is the ability to identify functional tissue in real time rather than relying exclusively on anatomical landmarks or preoperative imaging [5].

The variability of functional organization between individuals provides an important rationale for intraoperative mapping. Language areas cannot always be reliably predicted from conventional anatomical landmarks. Individual patients may demonstrate substantial differences in the cortical and subcortical organization of language, while slow-growing tumors may also be associated with functional reorganization [3,5]. Therefore, a standardized anatomical definition of eloquence may be insufficient to determine the safe limits of resection.

Intraoperative electrical stimulation mapping has consequently become an important component of surgery involving eloquent regions. It permits direct identification of functional cortical areas and subcortical pathways and allows the surgeon to modify the surgical trajectory according to functional responses [2]. During awake language mapping, several tasks may be employed, including object naming, counting, word repetition, reading, writing, and assessment of language syntax [1]. Motor mapping similarly permits identification of cortical and descending motor pathways that must be preserved during resection near the perirolandic region and corticospinal tract [2].

The importance of subcortical mapping has received increasing attention. Functional networks extend beneath the cortical surface through white-matter pathways, and injury to these structures may result in permanent neurological or language deficits. A detailed analysis of intraoperative language mapping literature demonstrated that approximately 40.4% of reported language errors occurred during subcortical stimulation, with certain phonemic and semantic errors occurring more frequently at the subcortical level [3]. These findings emphasize that preservation of eloquent function requires assessment of both cortical regions and deeper white-matter pathways.

Awake craniotomy has also been investigated in high-grade tumors, including glioblastoma. A systematic review and meta-analysis of 14 studies involving 278 patients undergoing awake craniotomy for supratentorial glioblastoma reported a pooled gross total resection rate of 74.7% and a pooled tumor-volume reduction of 95.3%. Although early postoperative neurological deficits occurred in 34.5% of patients, deficits persisting beyond three months were reported in only 1.9% [4]. However, these findings must be interpreted cautiously because the available evidence was largely derived from retrospective studies and the patients included were relatively young compared with the typical glioblastoma population [4].

The application of awake craniotomy therefore requires more than the ability to perform cortical stimulation. Appropriate patient selection, preoperative functional assessment, anesthetic planning, intraoperative communication, systematic language or motor testing, and interpretation of cortical and subcortical stimulation responses are all essential components of the procedure [1,5]. The technique must also account for potential intraoperative seizures, hemodynamic changes, patient intolerance, and the possibility of neurological deterioration [5].

This review examines the role of awake craniotomy in tumors involving eloquent brain regions, with particular emphasis on **indications and patient selection, surgical and anesthetic techniques, cortical and subcortical functional mapping, and postoperative functional outcomes**. The available evidence is considered in the context of the central surgical principle of achieving maximal safe resection while minimizing permanent neurological morbidity.

2. Indications for Awake Craniotomy

Awake craniotomy is principally considered when a brain tumor is located within or adjacent to cortical or subcortical regions responsible for critical neurological functions. Tumors involving potential language-eloquent regions represent an important indication for awake language mapping, even when the patient demonstrates normal language function before surgery [1]. Preoperative preservation of language therefore does not exclude the possibility that intraoperative mapping may be required.

The major functional domains relevant to awake surgery include **language and motor function**. Language mapping is particularly important for tumors involving the dominant frontal, temporal, and parietal regions or their associated subcortical pathways. Motor mapping is similarly important for lesions involving the primary motor cortex, perirolandic region, or descending corticospinal pathways [1,2].

The underlying principle is that the anticipated benefit of functional mapping should outweigh the physiological and logistical demands of maintaining patient cooperation during surgery. Awake craniotomy is therefore most valuable when preservation of function is a limiting factor in tumor resection and when intraoperative functional information can meaningfully influence the surgical strategy [5].

The procedure may be particularly advantageous for infiltrative gliomas because tumor boundaries frequently overlap with functional tissue. In low-grade gliomas, functional tissue may occasionally be located within the infiltrated tumor itself, making anatomical boundaries insufficient for determining the limits of resection [5]. Functional mapping allows the surgical boundary to be determined dynamically according to the patient's neurological responses.

Awake mapping may also be used for high-grade gliomas when the lesion is located in or near eloquent areas. Evidence from glioblastoma series suggests that substantial tumor removal can be achieved while maintaining a relatively low rate of persistent neurological deficits, although the quality of evidence remains limited [4].

3. Patient Selection and Preoperative Assessment

Appropriate patient selection is fundamental to successful awake craniotomy because the procedure depends on adequate patient cooperation throughout the functional mapping and resection phases [5]. Patient selection should therefore consider neurological status, cognitive and language function, psychological readiness, medical comorbidities, tumor location, tumor mass effect, and the anticipated requirements of intraoperative testing.

For awake language mapping, patients with supratentorial tumors located within or near potential language-eloquent regions should be considered even when preoperative language function is intact [1]. Baseline performance on language tasks is important because reliable intraoperative interpretation requires the patient to demonstrate adequate performance before stimulation. The literature reviewed by Morshed et al. indicates that patients considered for awake language mapping should generally have an acceptable baseline naming error rate, with greater preoperative impairment potentially limiting the reliability of intraoperative testing [1].

Preoperative neurological and neuropsychological assessment should therefore establish a functional baseline against which intraoperative and postoperative changes can be evaluated. Language assessment may include naming, comprehension, repetition, reading, writing, and related functions depending on the suspected location of the lesion [1,3].

Tumor-related mass effect is another important consideration. Significant cerebral edema or substantial midline shift may increase the risk associated with awake surgery. In such circumstances, optimization of the patient's neurological condition may be required before functional mapping is attempted. Where substantial mass effect persists, an awake procedure may not be appropriate and alternative approaches using preoperative functional imaging and other intraoperative monitoring strategies may be considered [1].

Preoperative imaging is used to establish the anatomical relationship between the tumor and functional structures. Functional magnetic resonance imaging, magnetoencephalography, positron emission tomography, and diffusion-based tractography can provide information regarding cortical activation and subcortical white-matter pathways [5]. These modalities improve preoperative planning and risk assessment but do not replace direct intraoperative stimulation mapping.

Diffusion tensor imaging and tractography can be particularly useful for visualizing the relationship between a tumor and major white-matter pathways. However, tractography is an anatomical reconstruction rather than a direct physiological assessment. Changes associated with tumor infiltration, distortion of white-matter pathways, and intraoperative brain shift may reduce its accuracy. Therefore, tractography should be considered complementary to, rather than a replacement for, intraoperative subcortical stimulation [2].

The patient's ability to tolerate the awake procedure must also be evaluated. Significant anxiety, inability to cooperate with testing, communication difficulties, and medical conditions that complicate conscious sedation may affect suitability. Medical comorbidities requiring careful consideration include conditions that may compromise respiratory function or make sedation difficult to administer safely [1].

The decision to perform awake craniotomy should consequently be individualized rather than based solely on tumor location. Patient-specific neurological status, comorbidities, expectations, ability to cooperate, and the anticipated functional risks of surgery should all be considered [5].

4. Anesthetic and Intraoperative Preparation

The success of awake craniotomy depends heavily on coordinated anesthetic and surgical management. Unlike conventional craniotomy under general anesthesia, the anesthetic technique must provide adequate analgesia and patient comfort during painful stages while allowing rapid transition to a sufficiently awake and cooperative state during functional mapping. The anesthetic plan should therefore be individualized according to the patient's medical condition, tumor location, expected duration of mapping, and anticipated intraoperative requirements [1,5].

Two principal anesthetic strategies have been described: **conscious sedation** and the **asleep-awake-asleep technique**. In conscious sedation, the patient remains spontaneously breathing without manipulation of the airway and receives titrated intravenous sedation. Propofol combined with remifentanil has been used extensively, with sedation reduced or discontinued before functional testing [5]. In the asleep-awake-asleep approach, the patient initially receives deeper anesthesia for positioning and craniotomy, is subsequently awakened for cortical and subcortical mapping, and is then returned to deeper anesthesia for tumor resection and closure [1].

The asleep-awake-asleep approach may permit greater sedation during painful portions of the procedure but can result in a longer emergence period before reliable functional testing can begin. Propofol-remifentanil and dexmedetomidine-remifentanil combinations have both been described. Comparative evidence indicates that dexmedetomidine-based conscious sedation may reduce respiratory adverse events compared with propofol-remifentanil while maintaining the ability to perform intraoperative mapping tasks [1].

Local anesthesia is an essential component of patient comfort. Scalp and incision infiltration, together with regional field blocks, can provide analgesia while avoiding excessive systemic sedation. In one established protocol, local anesthetic was used for pin fixation and regional infiltration, while conscious sedation was maintained at a level permitting the patient to respond appropriately to verbal stimulation [5].

Before functional mapping begins, sedative infusions should be reduced or discontinued sufficiently in advance to allow recovery of cognitive function. Residual effects of intravenous anesthetic agents can impair attention and language performance even after the apparent return of wakefulness. Therefore, assessment of patient wakefulness immediately before mapping is essential [1].

The surgical exposure itself is generally similar to that used during conventional craniotomy. The objective is to establish a surgical corridor that permits adequate tumor access while minimizing disruption of functional cortex. Small cortical exposures may be preferred in some cases, particularly when negative mapping is used to identify areas that can serve as relatively safe entry points [1].

During the procedure, continuous communication between the neurosurgeon, anesthesiologist, neuropsychologist, and patient is fundamental. The neuropsychologist or appropriately trained professional can administer standardized language or cognitive tasks while the surgeon performs stimulation and interprets functional responses. This multidisciplinary approach allows neurological changes to be recognized immediately and incorporated into the surgical decision-making process [1,2].

5. Cortical Functional Mapping

Intraoperative direct electrical stimulation remains the principal method for identifying functional cortical tissue during surgery involving eloquent regions. Non-invasive modalities such as functional MRI, MEG, DTI, and navigated transcranial magnetic stimulation provide useful preoperative information but do not possess the physiological specificity of direct cortical stimulation [2].

During cortical mapping, electrical stimulation is delivered through a bipolar or monopolar probe while the patient performs a predetermined functional task. A cortical site is considered functionally relevant when stimulation consistently produces a reproducible neurological disturbance corresponding to the function being tested [2].

For language mapping, the most frequently used task is **picture naming**. Other tasks include counting, word repetition, reading, writing, sentence completion, auditory naming, spelling, and assessment of syntax [1,2]. Selection of tasks should be tailored to the tumor location and the functions potentially threatened by resection. No single language task is universally optimal, and institutions differ considerably in their mapping protocols [2].

A positive language site may manifest as speech arrest, anomia, alexia, or another reproducible language disturbance. Repeated testing is important because transient errors can arise from fatigue, attention fluctuations, stimulation-related effects, or other factors unrelated to functional eloquence. Consequently, positive sites should be reproducible before being considered critical boundaries [2].

Cortical mapping is not limited to language. Sensorimotor mapping is used for tumors involving the perirolandic region and motor pathways. Stimulation of the motor cortex can produce movements of the face, upper limb, or lower limb, allowing the surgeon to identify the functional motor cortex and establish a safe surgical corridor [5].

The distinction between positive and negative mapping sites is important during tumor resection. Areas that do not produce a functional response during appropriately performed stimulation can potentially serve as entry points or corridors toward the tumor. Conversely, functionally positive sites should be preserved and treated as boundaries during subsequent resection [2].

The mapping process must also account for stimulation-induced after-discharges and seizures. Intraoperative electrocorticography can identify epileptiform activity following stimulation and can assist in determining an appropriate stimulation intensity. Limiting the intensity, duration, and repetition of stimulation can reduce the likelihood of seizure activity [1,2].

6. Language Mapping During Awake Craniotomy

Language mapping represents one of the most important applications of awake craniotomy because language function cannot be adequately assessed in an anesthetized patient. Direct cortical stimulation allows the surgeon to identify areas in which stimulation temporarily disrupts language performance and therefore provides functional information that can directly influence the extent and direction of tumor resection [1,2].

The language system is distributed across cortical and subcortical networks rather than being confined to a single anatomical location. Consequently, the traditional concept of isolated language centers is insufficient for planning surgery in many patients. Individual variability in language organization is substantial, making patient-specific intraoperative mapping particularly valuable [1,3].

Picture naming is commonly used because it provides a relatively simple and reproducible measure of lexical retrieval. Additional tasks can evaluate different components of language. Reading may identify disturbances in visual word processing, repetition can assess phonological and language pathways, writing can evaluate written language function, and sentence-based tasks can provide information regarding syntactic processing [1,3].

The selection of language tasks should correspond to the suspected functional anatomy of the tumor. For example, a lesion involving regions associated with reading may require a reading task, whereas lesions near frontal language regions may benefit from tasks assessing speech production and syntax. The available literature emphasizes that relying on a single task may fail to detect deficits involving other linguistic domains [3].

Importantly, language mapping should continue beyond the cortical surface. Subcortical stimulation may produce language disturbances even when cortical stimulation does not identify an obvious functional site. A review of intraoperative language mapping studies found that approximately 40.4% of reported language errors occurred during subcortical stimulation, highlighting the contribution of white-matter pathways to language function [3].

The presence of a positive cortical or subcortical language site can therefore substantially influence the surgical endpoint. Rather than pursuing anatomical tumor margins at the expense of neurological function, the surgeon can use functional responses to define an individualized resection boundary [2].

7. Subcortical Mapping

Subcortical mapping is an essential component of surgery involving eloquent brain tumors because functional pathways frequently extend beneath the cortical surface. Preservation of these white-matter structures is particularly important for language and motor function [2,3].

For motor-eloquent tumors, the corticospinal tract is a major structure of concern. Preoperative DTI tractography can demonstrate the expected relationship between the tumor and corticospinal pathway, but its accuracy may be affected by distortion of white-matter anatomy, selection of tractography seed regions, and intraoperative brain shift. Consequently, DTI should complement rather than replace physiological intraoperative mapping [2].

Motor-evoked potentials provide an additional method of assessing corticospinal tract integrity. Transcranial MEPs stimulate the motor cortex through the scalp and skull, while direct cortical stimulation can be performed after dural opening. The resulting electrical responses are recorded from limb muscles and provide continuous information regarding motor pathway function [2].

Direct subcortical stimulation can also be used during tumor removal. High-frequency monopolar stimulation is particularly useful for identifying motor pathways and can provide information regarding the proximity of functional subcortical structures. Bipolar stimulation may be employed when greater spatial specificity is required [2].

For language surgery, subcortical stimulation allows the surgeon to identify critical white-matter pathways involved in speech and language processing. Damage to these pathways can result in permanent language impairment even when the overlying cortical surface appears functionally silent. Therefore, cortical mapping alone may provide an incomplete assessment of the functional boundaries of an eloquent tumor [3].

As resection proceeds toward the deeper portion of the tumor, repeated subcortical stimulation allows the surgical team to continuously reassess the relationship between the resection cavity and functional pathways. This creates a dynamic safety boundary rather than relying exclusively on the preoperative anatomical estimate [2].

8. Integration of Mapping With Tumor Resection

The ultimate purpose of functional mapping is not merely to construct a map of the brain but to guide the surgical strategy toward **maximal safe resection**. The surgeon integrates preoperative imaging, neuronavigation, intraoperative cortical stimulation, subcortical stimulation, neuromonitoring, and real-time neurological responses to determine how far tumor removal can safely proceed [2].

The identification of functionally negative cortical regions can provide an appropriate corridor for initial corticectomy. Once tumor removal progresses toward functional tissue, positive cortical and subcortical stimulation responses become increasingly important in determining the limits of resection [2].

This approach is particularly relevant in infiltrative gliomas because tumor tissue may extend into regions that are functionally important but anatomically indistinguishable from surrounding brain. The surgeon must therefore balance the oncological objective of removing tumor with the functional objective of preserving neurological independence.

Motor monitoring provides an additional safety mechanism during resection near the corticospinal tract. A significant reduction in MEP amplitude, elevation of stimulation threshold, or disappearance of an evoked response may indicate potential motor pathway injury and should prompt immediate reassessment of the operative field [2].

Similarly, intraoperative language deterioration may provide an early warning that the surgical dissection is approaching functionally critical tissue. Intraoperative anomia and language production errors have been associated with acute postoperative language deficits, particularly when combined with preoperative language impairment [2].

The functional endpoint of surgery is therefore individualized. A gross total resection is desirable when achievable without unacceptable neurological risk, but a smaller residual tumor may be preferable when further resection would require injury to critical functional structures. This reflects the central principle of awake surgery: **the extent of resection should be maximized only within the limits established by functional preservation** [2,5].

9. Intraoperative Complications and Their Management

Although awake craniotomy is generally well tolerated, it presents specific anesthetic and surgical challenges. Complications may be broadly categorized as anesthetic-related, surgery-related, and patient-specific [5].

Hemodynamic changes, including hypertension, hypotension, and tachycardia, may occur during awake surgery. Although these changes have been reported more frequently in awake procedures than in procedures performed under general anesthesia, the reviewed literature indicates that they are generally manageable and do not necessarily result in clinically significant sequelae [5].

Intraoperative seizures are among the most important complications because cortical stimulation itself can provoke epileptiform activity. One reported series documented intraoperative seizures in approximately 5.6% of patients undergoing awake craniotomy, with most episodes being focal [5]. Stimulation-related seizures can frequently be managed by local cortical irrigation with cold solution, reduction or cessation of stimulation, and pharmacological treatment when required [1,5].

Electrocorticographic monitoring can identify after-discharges and help determine appropriate stimulation parameters. Reducing stimulation intensity and avoiding excessive repetition can decrease seizure risk [1,2].

Another potential complication is venous air embolism, although it appears to be uncommon. Prompt recognition requires close communication between the surgical and anesthetic teams [5].

Failure of awake craniotomy can also occur when the patient cannot cooperate adequately with functional testing. Reported causes include inadequate patient selection, medication-related impairment, communication difficulties, seizures, and respiratory complications. Careful preoperative assessment and precise timing of emergence from sedation are therefore important for maintaining intraoperative cooperation [2].

Despite these challenges, patient-reported satisfaction with awake craniotomy is generally high. Available evidence has reported satisfaction rates approaching 90%, suggesting that, with appropriate preparation and communication, the experience is acceptable to most appropriately selected patients [5].

10. Functional Outcomes

The primary objective of awake craniotomy in eloquent-area brain tumors is to maximize the extent of tumor removal without producing unacceptable neurological impairment. Functional outcome therefore represents one of the most important measures of procedural success. Intraoperative mapping provides the surgeon with real-time information about functional cortical and subcortical structures, allowing the extent of resection to be adapted to the patient's individual functional anatomy [1,2].

10.1 Extent of Resection

A major advantage of functional mapping is its ability to facilitate more extensive tumor removal while maintaining neurological function. Intraoperative stimulation mapping has been associated with more extensive resections and fewer late severe neurological deficits, despite being frequently used for tumors located in functional regions [2].

The principle is particularly important in infiltrative gliomas, where tumor margins may overlap with functional tissue. Rather than relying exclusively on anatomical boundaries, the surgeon can use functional responses to determine whether further resection is appropriate. This individualized approach allows resection to proceed through functionally negative tissue while respecting positive cortical and subcortical sites [2].

Evidence from glioblastoma patients further demonstrates the potential oncological value of awake surgery. A systematic review and meta-analysis of 14 studies involving 278 patients reported a pooled gross total resection rate of **74.7%** and a pooled mean reduction in tumor volume of **95.3%** [4]. These findings indicate that substantial tumor removal can be achieved even when glioblastomas are located in or near eloquent regions.

However, the extent of resection should not be interpreted independently of functional outcome. The objective of awake surgery is not maximal resection at any cost, but maximal **safe** resection. A functionally positive cortical or subcortical site may appropriately become the endpoint of resection when further tumor removal would threaten a critical neurological pathway [2].

10.2 Postoperative Neurological Deficits

Postoperative neurological deficits remain an important concern following surgery in eloquent brain regions. Importantly, postoperative deficits may be transient or persistent, and these outcomes should be distinguished when evaluating the safety of awake craniotomy.

In the glioblastoma meta-analysis, the pooled rate of early postoperative neurological deficits was **34.5%**, whereas the pooled rate of late deficits persisting beyond three months was only **1.9%** [4]. The difference between these figures suggests that a substantial proportion of early postoperative neurological disturbances may improve during subsequent recovery.

The possibility of transient neurological deficits does not necessarily indicate failure of functional mapping. Temporary deficits can result from surgical manipulation, edema, transient physiological disturbance, or other perioperative factors. Persistent deficits, in contrast, are of greater concern because they may substantially affect independence and quality of life [2,4].

Functional monitoring during surgery may help identify impending injury before permanent damage occurs. Changes in motor-evoked potentials, for example, may indicate potential corticospinal tract compromise and should prompt reassessment of the operative field and consideration of stopping or modifying resection [2].

10.3 Language Outcomes

Language preservation is a central outcome measure in awake craniotomy involving dominant-hemisphere tumors. The ability to test language during direct cortical and subcortical stimulation allows the surgical team to identify functionally important areas that might otherwise be indistinguishable from surrounding tissue [1].

The relationship between intraoperative language performance and postoperative outcome is particularly relevant. Intraoperative anomia and language-production errors have been associated with acute postoperative language deficits, especially in patients who already have preoperative language impairment

[2]. These observations emphasize the importance of carefully monitoring language performance throughout the procedure rather than assessing it only during the initial cortical mapping phase.

The systematic review by Collée et al. further demonstrates that language function is distributed across multiple cortical and subcortical locations. The review included **102 studies** and found that approximately **40% of reported language errors occurred during subcortical stimulation** [3]. This finding reinforces the importance of subcortical mapping in preventing postoperative language impairment.

The authors also identified localization patterns involving articulation and motor speech, phonology, reading, writing, and syntax and proposed modifications to the Dutch Linguistic Intraoperative Protocol (DuLIP) to improve location-specific task selection [3]. Such approaches may allow more precise functional testing according to the anatomical location of the tumor.

11. Patient Experience and Quality of Life

Preservation of neurological function is ultimately intended to preserve the patient's independence and quality of life. The benefit of awake craniotomy therefore extends beyond radiological tumor removal. A patient may have an extensive resection but still experience a poor overall outcome if the procedure produces a disabling neurological deficit [2].

One advantage of awake surgery is that the patient participates directly in the functional assessment. This allows the surgical team to evaluate language, motor performance, and other cognitive functions in real time and provides immediate feedback regarding the patient's neurological status [1,5].

Despite concerns that patients may find awake surgery distressing, available evidence indicates generally high patient satisfaction. Previous reports have described approximately 90% of patients as satisfied with the procedure, although some patients reported pain, discomfort, fear, or claustrophobia [5]. Appropriate patient counseling, careful anesthetic management, adequate local anesthesia, and continuous communication are therefore important components of the patient experience.

Awake craniotomy may also offer postoperative resource advantages. Earlier recovery and reduced requirements associated with general anesthesia may facilitate shorter hospital stays in appropriately selected patients [5]. However, these potential benefits should not become the primary reason for selecting awake surgery. Patient selection should remain based on the clinical indication, functional risk, medical condition, expectations, and values of the individual patient [5].

12. Awake Versus Asleep Mapping

Awake and asleep mapping are complementary approaches rather than universally interchangeable techniques. The choice depends on the tumor's location, the neurological functions at risk, the patient's preoperative condition, and their ability to cooperate during surgery [2].

Motor mapping can be performed under either awake or general anesthesia using direct stimulation and neurophysiological monitoring. However, higher cognitive functions such as language, visual perception, and spatial orientation require an awake and cooperative patient for direct intraoperative assessment [2].

The major advantage of awake mapping is therefore the ability to obtain immediate behavioral evidence of functional disruption. If stimulation of a cortical or subcortical region produces a reproducible language or motor response, the surgeon can modify the resection accordingly.

Asleep surgery may remain appropriate when the patient cannot safely or reliably participate in awake testing. Significant mass effect, inadequate baseline language performance, inability to cooperate, or other medical and anesthetic considerations may make an awake procedure unsuitable [1].
The available literature suggests that awake mapping may provide advantages in selected eloquent glioma patients, but the evidence should not be interpreted as demonstrating universal superiority of awake surgery for every tumor. The choice of approach should remain individualized [2].

13. Limitations and Challenges

Despite its advantages, awake craniotomy has several limitations. The procedure is highly dependent on appropriate patient selection and cooperation. Failure to maintain adequate wakefulness or communication can compromise functional testing and may require modification of the surgical or anesthetic plan [1,2].
Anesthetic management is another challenge. Excessive sedation may suppress cognitive performance and interfere with mapping, whereas inadequate sedation may produce anxiety, discomfort, agitation, or hemodynamic instability [1,5]. Achieving the appropriate balance requires close coordination between the anesthesiology and surgical teams.
Intraoperative seizures represent another limitation because electrical stimulation itself can provoke epileptiform activity. Although most stimulation-related seizures can be managed without major consequences, recurrent seizures may interfere with mapping or require conversion to deeper anesthesia [1,5].
Functional mapping also has inherent limitations. A negative stimulation site does not necessarily prove that the tissue is completely devoid of functional significance, while a positive response must be reproducible and interpreted in the context of stimulation parameters and patient performance [2].
Language mapping is particularly complex because language consists of multiple interacting processes rather than a single function. Picture naming alone may not adequately evaluate reading, writing, repetition, phonology, syntax, or speech initiation. The findings of Collée et al. support the use of multiple tasks tailored to the anatomical location and suspected linguistic function [3].
Finally, preoperative imaging techniques such as fMRI and DTI remain valuable but imperfect. DTI tractography can be affected by tumor-related distortion and intraoperative brain shift and therefore cannot substitute for physiological subcortical mapping [2].

14. Future Directions

Future development of awake craniotomy is likely to focus on improving the accuracy, efficiency, and individualization of functional mapping. Non-invasive functional imaging techniques are becoming increasingly sophisticated and may provide increasingly detailed preoperative information regarding functional networks [5].
Resting-state functional connectivity and network-based approaches may improve preoperative prediction of functionally important regions. However, the available literature emphasizes that these technologies currently complement rather than replace direct electrical stimulation during surgery [5].
Intraoperative language mapping may also become more systematic. The updated DuLIP framework proposed by Collée et al. provides a model for selecting language tasks according to the anatomical location and linguistic function being evaluated [3]. More standardized protocols may improve reproducibility between centers and allow more reliable comparisons of functional outcomes.

Technological advances in motor mapping are similarly expected to improve the integration of tractography, neuronavigation, MEP monitoring, and direct cortical and subcortical stimulation [2]. Combining multiple complementary techniques may provide more comprehensive protection of functional pathways during increasingly aggressive tumor resections.

Another important area for future research is the comparison of awake and asleep surgery using prospective randomized studies. Existing evidence, particularly in glioblastoma, is limited by retrospective study designs and heterogeneous patient populations [4]. High-quality prospective trials are therefore required to determine the precise clinical and oncological advantages of awake mapping across different tumor grades and anatomical locations.

15. Discussion

Awake craniotomy represents a functional approach to brain tumor surgery in which the limits of resection are determined not solely by anatomy but also by the patient's real-time neurological responses. This is particularly important for eloquent-area tumors, where conventional anatomical landmarks may not accurately predict the location of critical functional tissue [1,3].

The five reviewed references collectively support three major principles. First, **maximal safe resection** remains the fundamental surgical objective. Second, **direct electrical stimulation mapping** provides the principal intraoperative physiological method for identifying functional tissue. Third, **both cortical and subcortical mapping are necessary** because critical neurological functions are distributed across cortical networks and underlying white-matter pathways [1–3].

The available outcome data are encouraging. In glioblastoma, awake craniotomy has been associated with a pooled GTR rate of 74.7% and a pooled tumor-volume reduction of 95.3%, while persistent neurological deficits beyond three months occurred in 1.9% of patients in the available meta-analysis [4]. These findings suggest that extensive tumor removal can be achieved without a correspondingly high rate of permanent neurological morbidity.

Nevertheless, these findings should not be interpreted without considering the limitations of the evidence. The glioblastoma meta-analysis included only 14 studies involving 278 patients, and **all included studies were retrospective**[4]. Therefore, selection bias and differences in surgical expertise, mapping protocols, patient characteristics, tumor location, and outcome assessment may influence the reported results.

The role of awake surgery should consequently be understood as part of a broader functional neurosurgical strategy. Preoperative imaging, patient selection, anesthetic planning, direct cortical mapping, subcortical mapping, neurophysiological monitoring, and postoperative assessment must work together to achieve the desired balance between oncological control and functional preservation [1,2,5].

The most important conceptual development is the recognition that eloquence is not simply an anatomical property of a particular gyrus. Functional organization varies between individuals, and tumor growth may alter or reorganize existing networks. Awake mapping therefore provides a patient-specific functional assessment that can be integrated into the surgical decision-making process [3].

16. Conclusion

Awake craniotomy is an important technique for the surgical management of brain tumors involving or approaching eloquent cortical and subcortical regions. Its principal advantage is the ability to evaluate neurological function directly during tumor resection, allowing surgeons to maximize tumor removal while minimizing the risk of permanent functional injury [1,2].

Successful awake surgery requires appropriate patient selection, detailed preoperative assessment, individualized anesthetic management, reliable intraoperative cooperation, and systematic cortical and subcortical mapping. Language mapping should incorporate multiple tasks according to the functions potentially affected by the tumor, while motor mapping should integrate direct stimulation with appropriate neurophysiological monitoring [1,2].

Subcortical mapping is particularly important because functional pathways extend beyond the cortical surface and may represent critical boundaries during deep tumor resection [2,3]. Current evidence indicates that awake craniotomy can achieve substantial tumor removal with a relatively low rate of persistent neurological deficits, including in selected patients with glioblastoma [4].

However, the available evidence remains limited by retrospective study designs and heterogeneity among published studies. Further prospective research is required to establish the optimal selection criteria, mapping protocols, anesthetic strategies, and long-term functional and oncological outcomes.

Overall, awake craniotomy should be regarded not simply as a method of keeping the patient conscious during surgery, but as a **functional neurosurgical strategy for individualized maximal safe resection**. When appropriately indicated and performed by an experienced multidisciplinary team, it provides a powerful means of balancing oncological objectives with preservation of neurological function [1–5].

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