



Review Article

Advances in awake craniotomy for gliomas and epilepsy surgery with real-time language and motor mapping: A comprehensive review

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Abstract

Awake craniotomy (AC) has resurfaced as a revolutionary neurosurgical technique that facilitates maximal safe glioma resection and individualized epilepsy surgery by allowing real-time functional mapping. Direct patient involvement during surgery by AC equips surgeons with the option of preserving key cortical and subcortical networks, including language and motor functions, while attaining the best oncological or seizure control. This review integrates recent progress in awake craniotomy, highlighting anaesthesia protocols, integration of neurophysiology and neuroimaging, real-time cortical and subcortical mapping, and their applications in gliomas and epilepsy. Clinical results are measured in terms of survival, seizure freedom, and preservation of function. Patient selection, intraoperative heterogeneity, and mapping shortages are addressed among challenges, as well as future directions, such as connectome-based neurosurgery, artificial intelligence (AI), and brain–computer interfaces. The data indicate that AC, along with next-generation mapping techniques, will continue to be the core of precision neurosurgery for the next few decades.

Keywords: Awake craniotomy, Gliomas, Epilepsy surgery, Intraoperative mapping, Language preservation, Motor mapping, Connectomics, Brain–computer interface

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1. Introduction

Awake craniotomy (AC) is among the most important developments in neurosurgical practice, especially for intrinsic brain tumours and surgery for epilepsy. By facilitating intraoperative assessment of more complex cognitive, sensory, and motor functions, AC enables the identification and preservation of eloquent networks in resection.¹ Its rationale derives from the fact that maximal safe resection enhances overall survival in gliomas,^{2,3} while sparing eloquent tissue mitigates the risk of long-term disability and cognitive deterioration.

The return of AC is due to technical progress, such as functional mapping, integration of neuroimaging, neuro-navigator, and innovations in anaesthesia.^{4,5} In addition, the increasing use of AC in epilepsy attests to its application for individualized functional evaluation, facilitating resections with maximal seizure freedom and minimal language or motor impairment.^{6,7} This review gives an extensive

overview of AC developments, organized along historical contexts, anaesthetic and surgical strategies, functional mapping methods, uses in gliomas and epilepsy, limitations, and future directions.

2. Historical Development of Awake Craniotomy

The history of AC begins in the early 20th century, when Horsley and Penfield first developed intraoperative brain stimulation for epilepsy surgery.⁸ The method was first limited to epilepsy because of the requirement for accurate localization of the seizure focus. With improved cortical stimulation and anaesthetic methods, AC progressively began to include tumor resections in eloquent areas. Towards the end of the 20th century, the use of AC in glioma surgery was driven by the appreciation that extent of resection has a strong correlation with progression-free and overall survival.⁹ Pioneers like Duffau^{4,10} established that even eloquent diffuse low-grade gliomas could be safely removed using awake mapping. This changed the paradigm to

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functional preservation from the sole considerations of anatomy.

3. Anaesthetic Protocols and Patient Selection

Techniques: Two main anaesthetic approaches predominate AC:

1. **Asleep–awake–asleep (AAA):** The patient is induced under general anaesthesia, is awakened for cortical mapping, and is re-anaesthetized for closure.¹¹
2. **Monitored anaesthesia care (MAC):** Sedation, but not unconsciousness, is maintained during the procedure, with individually adjusted sedation by short-acting drugs like propofol, remifentanyl, or dexmedetomidine.¹²

The selection relies on patient comorbid conditions, projected time to map, and surgeon-anaesthesiologist preference. Table 1 summarizes the comparison of anaesthetic protocols in awake craniotomy.

Table 1: Comparison of anaesthetic protocols in awake craniotomy

Feature	Asleep–Awake–Asleep (AAA)	Monitored Anaesthesia Care (MAC)
Patient state	General anaesthesia → awake → asleep	Sedated but cooperative throughout
Induction	Propofol, remifentanyl	Dexmedetomidine, propofol, remifentanyl
Airway management	Intubation or LMA	Spontaneous breathing
Advantages	Airway secure, stable for long surgeries	Continuous cooperation, shorter recovery
Limitations	More complex transitions, delayed wake-up	Anxiety, risk of airway compromise

3.1. Patient selection

Most suitable candidates are patients with lesions adjacent to eloquent areas who can cooperate with intraoperative activities. Contraindications are severe anxiety, communication impairment, or medical instability.¹³ Preoperative neuropsychological evaluation is important to establish baseline function and develop intraoperative testing strategies.¹⁴

3.2. Real-time functional mapping

Functional mapping is the central component of AC. It involves patient testing and intraoperative stimulation to define eloquent areas.

1. **Cortical mapping:** The gold standard for cortical mapping is direct electrical stimulation (DES). In DES, individual areas of the brain are stimulated while patients carry out activities (speaking, movement, counting). Interruptions in performance reveal areas of function that must be spared.¹⁵ Progress involves high-frequency stimulation protocols that increase sensitivity and decrease after-discharges.¹⁶
2. **Subcortical mapping:** White matter tracts are commonly involved in glioma resections. Stimulation of the subcortical level enables marking of important pathways like the corticospinal tract and arcuate fasciculus.^{4,17} Avoids postoperative hemiparesis or aphasia.
3. **Language and higher cognitive mapping:** From early picture-naming tasks to more complex tests measuring semantic, phonological, and syntactic processing.¹⁸ Mappings of executive functions and multitasking skills increasingly highlight the distributed nature of cognition.¹⁹

4. Neuroimaging and Technological Integration

1. **Preoperative imaging: Diffusion tensor imaging (DTI):** Maps white matter tracts for surgery planning.²⁰
2. **Functional MRI (fMRI):** Maps cortical activation patterns, but less valid than DES.²¹

4.1. Intraoperative technologies

1. **Neuronavigation:** Offers real-time anatomical guidance, albeit impacted by brain shift.
2. **Intraoperative MRI and ultrasound:** Correct for anatomical change on resection.²²
3. **Fluorescence-guided surgery (5-ALA):** Assists in demarcating tumor margins, generally in conjunction with AC.²³

4.2. Use in glioma surgery

AC is especially useful in low- and high-grade gliomas in eloquent regions, as summarized in Table 2.

1. **Extent of Resection (EOR):** Numerous studies indicate AC allows greater EOR without more deficits than asleep surgery.^{3,5}
2. **Survival Outcomes:** AC is associated with better progression-free and overall survival.²
3. **Neurocognitive Preservation:** Mapping preserves language and motor function and mitigates long-term disability.⁴

Table 2: Clinical outcomes of awake craniotomy in gliomas

Outcome	Awake Craniotomy	Asleep Craniotomy
Extent of Resection (EOR)	Higher, esp. near eloquent regions	Lower in eloquent regions

Post-op deficits (early)	15–30% (mostly transient)	Comparable
Post-op deficits (permanent)	<5–10%	Higher risk if eloquent areas involved
Survival benefit	Yes (correlated with EOR)	Lower
Quality of Life	Preserved (language/motor intact)	Often reduced in eloquent resections

5. Applications in Epilepsy Surgery

In epilepsy, AC makes individualized resections possible, as collated in Table 3:

- 1. Temporal lobe epilepsy:** Allows for pre-resection mapping of memory and language.⁷
- 2. Extratemporal epilepsy:** Especially beneficial in frontal lobe surgery in which motor and executive networks are endangered.⁶

Seizure freedom rates are equivalent or better than asleep surgery, with more favourable preservation of function.²⁴

Table 3: Awake craniotomy in epilepsy surgery: Outcomes

Type of Epilepsy	AC Application	Key Outcomes
Temporal Lobe Epilepsy	Memory & language mapping before resection	High seizure freedom; cognitive preservation
Frontal Lobe Epilepsy	Motor & executive function mapping	Improved seizure freedom with function preservation
Extratemporal Epilepsy	Task-specific mapping	Comparable seizure outcomes; fewer deficits

6. Discussion

Awake craniotomy has become increasingly prominent as an important surgical technique for gliomas and epilepsy because it can optimize resection with preservation of vital neurological function. The combination of real-time language and motor mapping has been especially revolutionary, providing intraoperative information regarding each patient's brain network organization that preoperative imaging cannot always assure.^{4,5}

- 1. Extremity of resection vs. functional preservation:** The inherent dilemma in glioma and epilepsy surgery is the balance between aggressive resection and functional preservation. Various studies show that the degree of resection directly correlates with overall survival for gliomas and freedom from seizures for epilepsy.^{2,6} Yet, resection beyond functional limits jeopardizes permanent deficits that compromise quality of life to a large extent. Awake craniotomy

solves this problem by permitting real-time language, motor, and memory pathway mapping, with resection margins adjusted to the patient's individual functional anatomy.

- 2. The use of cortical and subcortical mapping:** Classic cortical stimulation methods, though valuable, have the limitation of variability of functional anatomy between patients. Subcortical mapping during awake surgeries broadened the horizon of safe resections, especially by defining critical white matter tracts like arcuate fasciculus and corticospinal tract.¹⁴ This has threatened to overthrow the traditional concept of eloquent "cortical centers" in favor of the distributed and dynamic character of functional networks. Such observations are increasingly transforming neurosurgery from a localization to a connectivity paradigm.
- 3. Anaesthetic and logistical considerations:** Awake craniotomy success is directly related to anaesthetic management and patient cooperation during surgery. Both asleep–awake–asleep (AAA) and monitored anaesthesia care (MAC) modalities are commonplace, with data indicating similar safety and efficacy.^{11,12} Proper selection of patients preoperatively, psychological optimization, and multidisciplinary planning are crucial in achieving optimal results. Anxiety, however, fatigue, or intolerance of wakefulness continue to be obstacles, precluding a subgroup of patients from this technique.
- 4. Comparative effectiveness and limitations:** While awake craniotomy is clearly superior, it is not equally superior in every case. Non-eloquent lesions can be safely treated under general anaesthesia, and in some patients, awake procedures can be psychologically or airway hazardous. Further, the evidence comes mostly from high-volume, specialty centers with concerns of generalizability to smaller institutions or resource-poor settings. Standardization of the mapping protocol and outcome measures is an unmet need in the literature.

7. Directions

New developments hold the promise to further improve awake surgery. Brain–computer interface technologies and connectome-based neurosurgery can potentially allow surgeons to map higher-order functions intraoperatively, extending beyond language and motor domains.^{25,26} Artificial intelligence for intraoperative data, including automated speech recognition or neurophysiological signal analysis, has the potential to enhance mapping procedures' objectivity and efficiency. At the same time, multicentred registries and standardised outcome reporting will be key to progressing evidence-based practice and facilitating global applicability. New trends will reinforce AC outcomes (see Table 4).

1. **Connectome-based surgery:** Incorporation of entire-brain network models to assist with resections outside focal eloquent regions.¹⁴
2. **Artificial intelligence:** Machine learning intraoperative speech analysis and mapping prediction.²⁵
3. **Brain-computer interfaces (BCIs):** Intraoperative application to track real-time connectivity changes.²⁶
4. **Standardization of protocols:** International efforts towards harmonizing mapping tasks and anaesthetic protocols.

Table 4. Future directions in awake craniotomy

Innovation	Application	Potential benefit
Connectome-guided neurosurgery	Network-level resection planning	Minimize cognitive/functional deficits
Artificial Intelligence	Automated intraoperative speech analysis	Faster, more accurate mapping
Brain-Computer Interfaces (BCI)	Real-time connectivity monitoring	Adaptive resection guidance
Standardized mapping protocols	Cross-centre harmonization	Improved reproducibility, outcomes

8. Challenges and Limitations

Notwithstanding its advantages, AC also has several limitations:

1. **Patient tolerance:** Intraoperative distress and anxiety continue to pose obstacles.¹³
2. **Brain shift:** Decreases neuro-navigation accuracy.²²
3. **Task variability:** The absence of standardized cognitive protocols makes comparisons of studies difficult.¹⁸
4. **Resource intensive:** Is dependent on skilled multidisciplinary teams and specialized facilities.

8.1. Clinical implications

The development of awake craniotomy from a specialized epilepsy procedure to a standard neurosurgical approach for gliomas and other eloquent lesions has several significant clinical implications.

1. **Optimizing the degree of resection while maintaining function:** Awake procedures allow for oncologically significant resections to be accomplished by the surgeon without sacrificing critical neurological function. In gliomas, in which survival is directly related to the degree of resection, awake mapping clearly has an advantage by achieving tumour clearance while preserving language, motor, and cognitive function.

2. **Personalized neurosurgery:** The capacity to customize resection based on live patient performance is an extension of a larger trend toward precision medicine. Awake craniotomy enables personalized mapping of functional networks, considering inter-patient heterogeneity in cortical and subcortical organization.
3. **Integration into epilepsy surgery:** In drug-resistant epilepsy patients, awake procedures enhance the localization of epileptogenic regions and minimize postoperative neurocognitive impairment risk. This translates to improved seizure control and maintained quality of life, especially for temporal and frontal lobe operations.
4. **Multidisciplinary team approach:** Effective awake craniotomy demands multidisciplinary collaboration among neurosurgeons, neuro anesthesiologists, neuropsychologists, and speech-language pathologists. This emphasizes the importance of specialized centers with standardized protocols and trained staff to ensure maximum outcomes.
5. **Eligibility expansion:** Improvements in anaesthetic technique (e.g., monitored anaesthesia care and asleep-awake-asleep methods) have increased the population eligible for awake surgery, including very elderly patients and those with severe comorbid conditions who were previously deemed unsuitable.
6. **Health economics and accessibility:** By decreasing postoperative complications, hospital stay, and long-term disability, awake craniotomy has the potential to make neurosurgical care cost-effective. Nevertheless, there are differences in access, especially in low- and middle-income settings where technical competence and facilities might be inadequate.

9. Conclusion

Awake craniotomy has progressed from an advanced surgical technique to a dominant paradigm of accurate neurosurgery in the treatment of gliomas and pharmaco-resistant epilepsy. Enabling real-time communication between the operating team and awake patient creates an ideal situation for optimizing the extent of removal while at the same time protecting critical functions like language, motor function, and memory. This two-way advantage—oncological or epileptogenic control plus maintenance of neurological integrity—has solidified awake surgery as an excellent option for lesions in eloquent brain areas. Technological advances, including cortical and subcortical mapping, multi-modal functional imaging integration, and anaesthetic refinement, have greatly extended the scope of awake craniotomy. Addition of real-time monitoring and advanced neuropsychological testing during surgery has further improved the accuracy and safety of resections. Outcomes continuously show that awake surgeries are correlated with

greater resection rates, better seizure outcomes, fewer permanent deficits, and better long-term quality of life in comparison to the conventional asleep procedures. However, awake craniotomy is not without issues. Patient selection is still key, with psychological readiness and tolerance hugely affecting intraoperative compliance and outcomes. Heterogeneity in mapping protocols and cognitive testing paradigms between institutions continues to hinder standardization and generalizability of findings. Furthermore, technical requirements of awake surgery require high-level multidisciplinary teams and continue to be resource-intensive, especially in low-resource environments.

Tomorrow will bring awake craniotomy closer to the integration of connectome-guided surgical planning, intraoperative analytics driven by artificial intelligence, and brain–computer interface (BCI) technologies. These technologies will enable the expansion of the application of real-time functional mapping from simple language and motor functions to more complex areas like executive function, social cognition, and emotion regulation. Standardized international protocols and multicentred registries will also be crucial for benchmarking performance and driving evidence-based best practices. In short, awake craniotomy is a technical as well as philosophical advancement in neurosurgery—from sacrificing disease at any cost to maintaining the integrity of patient identity and quality of life while maximizing therapeutic benefit. With advancing times, awake craniotomy will continue to illustrate the tenets of precision medicine in neurosurgery: precision not just for the disease but also to the individualized functional and cognitive blueprint of every patient's brain.

10. Source of Funding

None.

11. Conflict of Interest

None.

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