

The Role of Connectomics and Advanced Cortical Mapping in Awake Craniotomies for Eloquent Area Tumors: A Comprehensive Review

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ABSTRACT

Purpose to explore the challenges and solutions in surgical management of brain tumors located in eloquent areas, with the goal of maximizing extent of resection (EOR) while preserving neurological function. New framework for neuro-oncology: The connectome-driven paradigm shift from localization to network understanding of the brain. Abstract: This comprehensive review evaluates advanced cortical mapping, resting-state functional MRI (rs-fMRI), and high-definition tractography integrated during awake craniotomies. We conducted a critical review of the literature, with an emphasis on cutting-edge studies examining how preoperative connectomic profiling used in combination with intraoperative direct electrical stimulation (DES) can inform maximal safe resection. By utilizing advanced mapping to identify and spare important subcortical white matter tracts, the risk of permanent postoperative deficits can be minimized. However, up to the present date current data provides evidence indicating substantial improvement in functional outcomes and overall survival after connectome-guided awake craniotomies with preservation of higher-order cognitive networks. Nevertheless, the task of routinely deploying these technologies requires standardized protocols and solid neuroinformatics software tools.

KEYWORDS: Connectomics; Awake Craniotomy; Cortical Mapping; Eloquent Tumors; Direct Electrical Stimulation; fMRI; Tractography.

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INTRODUCTION

The common goal in neuro-oncological surgery is obtaining the maximally safe extent of resection (EOR), which has proven crucial for prolonged progression-free and overall survival both in low-grade and high-grade gliomas patients (1). On the other hand, when tumors invade highly eloquent cortical and subcortical regions (motor, language or visuospatial areas), the risk of significant postoperative morbidity from aggressive resection is elevated (2). Traditionally, the brain was regarded in terms of a strict localizationist perspective wherein specific functions were confined to discrete patches across the cortex. Such view would also lead to the tendency of underestimating the complex, distributed processing power of the brain (3).

Connectomics has begun to spark advances in understanding cerebral architecture over the last decade. The human connectome lays out the brain as a rich, topological network of structural and functional connections (4). This network-

based model suggests that agonising postsynaptic deficits are not due to simple lesions of one particular cortical epicenter, but to disconnection from complicated white matter pathways connecting remote functional nodes (5). In surgical practice, this has increased the role of subcortical mapping in parallel with conventional cortical stimulation. This method has now become the gold standard in real time mapping of eloquent area, which is its use during awake craniotomy and intraoperative direct electrical stimulation (DES) (6). In an awake procedure. integration of preoperative connectomic data, derived from advanced diffusion tensor imaging (DTI) and resting-state functional MRI (rs-fMRI), into the neuronavigation system allows for individualization of mapping of a patient's unique functional neuroanatomy (7). This review systematically reviews the clinical use, neurosurgical techniques, and functional outcome impact of connectomics in conjunction with

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sophisticated cortico-cortical mapping using awake craniotomy Ondrovic et al.

PATHOPHYSIOLOGY AND NEURAL PLASTICITY

Gliomas often exhibit a slow, infiltrative growth pattern, particularly in WHO Grade 2 and 3 tumors. This slow progression frequently triggers neuroplasticity, allowing the brain to recruit perilesional or contralateral networks to maintain function, a phenomenon well-documented in connectomic studies (8). Consequently, anatomical landmarks are notoriously unreliable in glioma surgery, as

the functional cortex may have reorganized significantly prior to clinical presentation (9).

Preoperative connectomic analysis utilizes DTI to perform tractography, visualizing vital subcortical fasciculi such as the arcuate fasciculus, superior longitudinal fasciculus, and corticospinal tract (10). Furthermore, rs-fMRI identifies the synchronous spontaneous fluctuations of interconnected regions, delineating vital networks like the Default Mode Network (DMN) and the Central Executive Network, which are crucial for higher cognitive and executive functions (11).

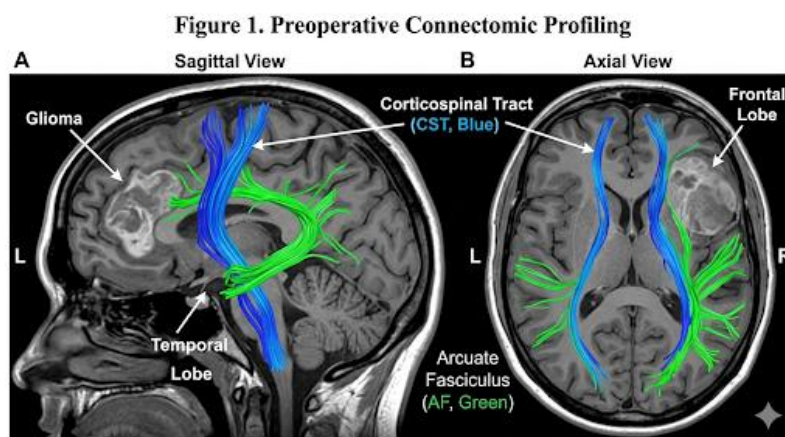


Figure 1. Preoperative Connectomic Profiling.

(Placeholder for an image showing an MRI with colored DTI tractography highlighting the corticospinal tract and arcuate fasciculus displaced by a frontotemporal glioma).

SURGICAL TECHNIQUES AND INTRAOPERATIVE MAPPING

The success of connectome-guided awake craniotomy hinges on rigorous preoperative planning and precise intraoperative execution. The patient is typically managed with an asleep-awake-asleep (AAA) anesthetic protocol or monitored anesthesia care (MAC) using target-controlled infusions of propofol and dexmedetomidine (12).

Once the dura is opened, bipolar DES is applied to the

cortical surface. The integration of augmented reality (AR) or advanced microscope-based neuronavigation allows the surgeon to overlay the preoperative connectomic blueprint directly onto the surgical field (13). The patient performs continuous cognitive, motor, or language tasks designed by a neuropsychologist. When DES temporarily disrupts a functional node or tract (inducing a speech arrest, paraphasia, or motor inhibition), the surgeon places a sterile tag, effectively defining the functional boundary of the resection (14).

Figure 2. Intraoperative Cortical and Subcortical Mapping via Direct Electrical Stimulation (DES)

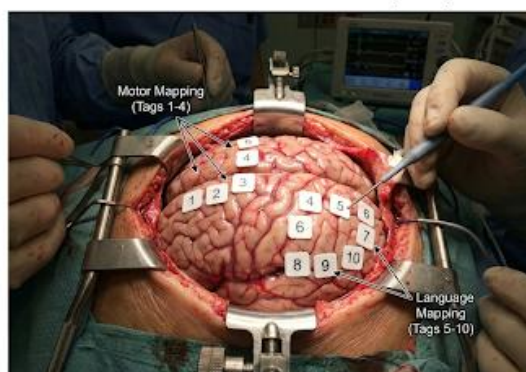


Figure 2. Intraoperative Cortical and Subcortical Mapping via Direct Electrical Stimulation (DES).

Table 1. Modalities of Advanced Cortical and Subcortical Mapping

Mapping Modality	Primary Function Monitored	Key Anatomical Tracts / Networks	Clinical Impact (EOR / Safety)
Cortical DES	Primary motor, sensory, speech articulation	Precentral gyrus, Broca's area	Prevents dense hemiparesis and motor aphasia (1, 6)
Subcortical DES	Subcortical connectivity during resection	Corticospinal tract, Arcuate fasciculus	Maximizes safe deep margins; prevents permanent disconnection (10, 14)
fMRI (Task-based)	Preoperative functional localization	Language dominance, motor hand knob	Guides craniotomy size and DES starting points (7, 11)
rs-fMRI & DTI	Global network preservation	Superior longitudinal fasciculus, DMN	Preserves neurocognitive baseline and executive function (4, 15)

CLINICAL OUTCOMES AND EXTENT OF RESECTION

The literature overwhelmingly supports the superiority of mapping-guided resections. Large retrospective cohorts and meta-analyses indicate that patients undergoing awake craniotomy with DES have higher rates of gross total resection (GTR) and significantly lower rates of permanent late severe neurological deficits (typically <2-4%) compared to asleep craniotomies under general anesthesia (15).

More recently, the specific inclusion of connectomic data has shown promise in preserving higher-order neurocognitive functions—such as working memory, emotional recognition, and visuospatial attention—that are frequently neglected in standard motor-language mapping (16). By avoiding the transection of functional hubs identified on preoperative network analysis, patients demonstrate accelerated postoperative rehabilitation and higher rates of return to professional employment (13, 16).

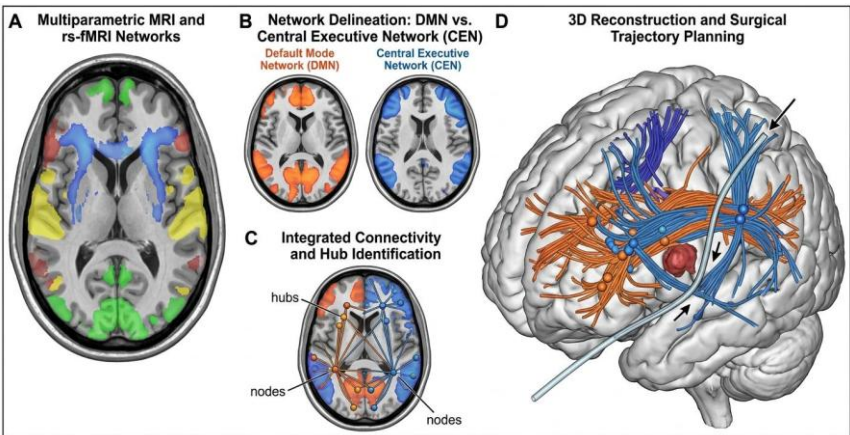


Fig. 3. Functional brain network mapping via resting-state fMRI for strategic surgical trajectory design. (11)

Figure 3. Resting-State fMRI (rs-fMRI) and Functional Network Preservation

CONCLUSION

The integration of connectomics and advanced cortical mapping in awake craniotomies represents a monumental shift in neuro-oncology. By visualizing the brain as a dynamic network rather than a static anatomical map, neurosurgeons can push the boundaries of maximal safe resection in highly eloquent areas. While DES remains the irreplaceable intraoperative arbitrator of function, preoperative structural and functional connectomics provide the essential roadmap. Future research must focus on the standardization of neuroinformatics tools, the application of machine learning for automated tractography, and the long-term neurocognitive evaluation of patients to solidify connectomics as a universal standard of care in glioma surgery

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