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Original Article

Creating Real-Time Intraoperative Brain Mapping Tools That Don’t Disrupt Surgery

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I. ABSTRACT BACKGROUND

A. Neurosurgery and Its Purpose

Neurosurgery is a medical field focused on treating conditions that affect the brain, spinal cord, and nervous system. This can include removing tumors, treating epilepsy, or repairing brain injuries. Surgeons need to be extremely precise because even small mistakes can result in permanent damage. This precision is why mapping brain functions during surgery is extremely important & necessary, it helps neurosurgeons identify areas that must be preserved, like those responsible for speech, movement, or memory.

B. The Challenge of Navigating the Brain During Surgery

The brain is not a static organ. It moves and shifts during surgery due to factors like gravity, fluid pressure changes, and the surgery itself. This constant shifting can make navigation extremely hard for surgeons, especially because areas identified in pre-surgical imaging may no longer align with the actual brain tissue being operated on.

C. The Need for Brain Mapping Tools

During surgery, doctors rely on mapping technologies to locate areas of the brain responsible for key functions. Traditional methods, like stimulating areas of the brain to see how the body reacts, are useful but have their cons. These methods often don’t capture the real-time changes happening in the brain. For this reason, there’s a growing demand for tools that can provide live, continuous mapping to guide surgeons during & through surgery.

D. The Role of Electrophysiology vs. Hemodynamics in Mapping

When mapping the brain, surgeons can look at electrical activity (EEG, ECoG) or blood flow responses (fMRI, fNIRS). These measure completely different things. Electrical activity shows instant neuron firing—great for timing, poor for precision. Hemodynamics show where blood rushes to support brain activity—better for spatial resolution, but slower and less responsive. Understanding this tradeoff shows why a perfect mapping tool doesn’t exist yet.

E. Brain Mapping in Awake vs. Asleep Surgeries

Some brain surgeries are done while the patient is awake to allow surgeons to test real-time responses—like asking a patient to speak while parts of their brain are stimulated. But not every surgery can be done awake, and this approach can be traumatizing or medically risky. In asleep surgeries, surgeons lose this real-time feedback, this creates a need for more accurate & passive tools.

F. Why One-Size-Fits-All Mapping Doesn’t Work

Everyone’s brain is different. Two patients might have language function in slightly different spots, or a tumor may have pushed brain regions into new areas. This makes static, standardized brain maps basically useless in a real surgery. That’s why personalized, dynamic mapping tools are the only real way forward

G. Mechanisms of the Motor Cortex:

The motor cortex is one of the most crucial areas involved in planning, controlling & carrying out voluntary movements. It’s located in the posterior portion of the frontal lobe, just in front of the central sulcus, and is divided into two main regions — the primary motor cortex (M1) and the premotor areas.

- The primary motor cortex acts as the main command center. It sends direct signals to the spinal cord that activate specific muscles in the body. These signals travel through long neural pathways called corticospinal tracts, and the intensity and direction of these signals determine the force and precision of muscle contractions.
- The motor cortex is also organized somatotopically, meaning different parts of it control different areas of the body.

Larger sections are devoted to areas requiring more precision, like the hands and face, while less detailed regions control the torso or legs.

- The premotor cortex and supplementary motor area help plan complex movements before they're executed. They take into account sensory cues, memory, and spatial awareness to prepare the right motor response — especially for coordinated sequences like playing an instrument or typing for example.

In the context of neurosurgery, the motor cortex needs to be mapped in extreme detail to avoid causing damage or loss of function. Damage or disruption to this region can lead to partial or complete paralysis of the corresponding body part.

H. Mechanisms of the Somatosensory Cortex:

The somatosensory cortex is responsible for processing sensory input, things like touch, temperature, pressure, etc. It's located in the parietal lobe, directly behind the central sulcus, and works hand-in-hand with the motor cortex to create fluid movement and perception.

- The primary somatosensory cortex (S1) is arranged just like the motor cortex — in a somatotopic map. Each section corresponds to a specific part of the body, with more cortical space dedicated to sensitive areas like the lips, fingers, and face.
- When sensory receptors in the skin, muscles, or joints are stimulated, electrical signals travel through the spinal cord and thalamus before finally reaching the somatosensory cortex. Once there, these signals are interpreted into actual sensations like pain, vibration, or pressure.
- The somatosensory cortex isn't just for feeling — it also helps with fine motor coordination. For example, to grasp an object precisely, your brain must constantly process how the object feels in your hand and adjust your grip. This back-and-forth feedback between sensory and motor regions is extremely important for smooth & precise movement.

In surgery, damaging the somatosensory cortex could result in loss of sensation & things like abnormal touch perception. For this reason, accurately identifying and protecting this area is extremely important, especially in surgeries involving tumors or epileptic lesions near the parietal lobe.

I. Mechanisms of the Visual Cortex

The visual cortex, located in the occipital lobe at the back of the brain, is the area responsible for receiving and processing visual information from the eyes. Even though the eyes physically gather light and form the image, it's the visual cortex that actually interprets all of it into something meaningful.

- Visual input starts at the retina, where light is converted into electrical signals by photoreceptors. These signals then travel via the optic nerve, cross at the optic chiasm, and continue to the lateral geniculate nucleus (LGN) of the thalamus before reaching the primary visual cortex (V1).
- The visual cortex itself is divided into multiple areas (V1 through V5), each handling different aspects of sight. For example:
    1. V1 processes basic information like orientation, edges, and contrast.
    2. V2–V3 starts combining this information to detect patterns or depth.
    3. V4 specializes in color processing.
    4. V5 is mainly responsible for detecting motion.

- information from both eyes is combined to create depth perception and spatial awareness. The visual cortex then sends this processed information to other brain areas for higher-level functions as well.

In surgery, damaging or stimulating parts of the visual cortex can lead to partial or complete vision loss & even hallucinations, or disruptions in how the brain interprets motion and space. So for surgeries near the occipital lobe — like removing tumors or malformations — accurate brain mapping is extremely important to avoid these complications.

J. Mechanism of the Broca's Area

Broca's area, located in the posterior part of the frontal lobe (typically the left hemisphere, especially in right-handed individuals), is the brain's primary center for language production. It's responsible for forming speech, structuring sentences, and coordinating the muscles used for talking, like those in the lips, tongue, and vocal cords.

- Broca's area doesn't just manage motor aspects of speech, it also plays a huge role in the cognitive processing of language—things like grammar, word selection, and syntactic structuring.

- It works closely with Wernicke's area, which handles language comprehension. The two are connected by a bundle of nerve fibers called the arcuate fasciculus. When you want to respond to something you heard, the signal flows from Wernicke's area to Broca's area, and then to the motor cortex for vocalization.

Damage to this area during surgery — especially in procedures near the inferior frontal gyrus — can result in Broca's aphasia, where a patient knows what they want to say but struggles to form words or sentences. Their comprehension remains mostly intact, but speech becomes broken.

K. Mechanisms of the Hippocampus

The hippocampus is a crucial structure primarily involved in memory formation. It's located in the medial temporal lobe, and functions as a hub for converting short-term memories into long-term ones, as well as processing and storing sensory information.

- The hippocampus is essential for episodic memory (memories of specific events) and declarative memory (facts and information). It works with the prefrontal cortex to process the information needed for decision-making and planning.
- This structure works through a process called synaptic plasticity, where repeated stimulation of certain neural pathways strengthens the connections between neurons. One key mechanism is long-term potentiation (LTP), a process that enhances synaptic transmission, facilitating learning and memory storage.

Damage to the hippocampus, whether through surgery or injury, can lead to anterograde amnesia, where a person cannot form new memories after the damage occurs. For example, patients may still remember their past but struggle to recall events or learn new information.

L. Current Strategies & Their Limitations

a) Electrocortical Stimulation (ECS)

Electrocortical stimulation involves directly stimulating the cortical surface of the brain using electrodes during surgery. By applying low-voltage electrical pulses, surgeons can identify brain regions responsible for essential functions like speech, motor skills, and sensory processing. The patient could also be awake during this.

i) *How it works:*

- Electrodes are placed on the exposed brain surface.
- Small electrical pulses are delivered to specific areas.
- The patient is asked to perform tasks, such as moving a limb or speaking, while the surgeon monitors for any disruptions in function caused by stimulation.

ii) *Limitations:*

- Invasive: This technique needs open brain surgery, which is inherently risky and can lead to complications like infection or hemorrhage.
- Limited Mapping Area: ECS can only map the areas directly accessible on the cortical surface, leaving deeper brain regions unaddressed.
- Patient Discomfort: Although patients may be awake, they are often under sedation and can experience anxiety or discomfort, especially when their brain is being stimulated.

iii) *Short-Term Results:*

ECS can provide only temporary information during surgery and does not offer long-term insights into brain function.

b) Functional Magnetic Resonance Imaging (fMRI)

Functional MRI (fMRI) is a non-invasive technique that measures brain activity by detecting changes in blood flow, a proxy for neuronal activity. It is used to map areas of the brain responsible for specific functions such as motor skills, language, and sensory perception. fMRI is typically performed prior to surgery to create a brain map that helps guide the neurosurgeon.

i) *How it works:*

- The patient is placed in an MRI scanner, where brain activity is measured while they perform specific tasks (e.g., moving a finger or speaking).
- Changes in blood flow are detected, indicating regions of the brain that are active during the task.

ii) *Limitations:*

- Preoperative Only: fMRI can be used only before the surgery, not during it, which limits its utility for real-time guidance.
- No Direct Stimulation: Unlike ECS, fMRI does not provide the ability to directly stimulate the brain during surgery to confirm the functions of various regions.
- Resolution Limitations: While fMRI is quite effective at detecting large-scale brain activity, it lacks the fine spatial resolution needed to identify small or very specific regions of interest.

iii) *Movement Artifacts:*

The patient needs to remain still during the scan, which can be difficult for some individuals, especially when the task requires motor activity.

c) Intraoperative Neurophysiological Monitoring (IONM)

Intraoperative neurophysiological monitoring (IONM) is a technique used during surgery to continuously monitor the functional integrity of the brain and spinal cord. It involves placing electrodes on the patient's scalp, spinal cord, or brain during surgery to record electrical activity in real-time. IONM is primarily used to monitor motor pathways, ensuring that no critical areas are damaged during the procedure.

i) *How it works:*

- Electrodes are placed on the patient's skin or directly onto the brain tissue.
- During surgery, electrical activity is monitored while the patient performs specific tasks or while the surgeon manipulates brain tissue.
- The system continuously alerts the surgeon if any motor function is disrupted, helping prevent damage to critical pathways.

ii) *Limitations:*

- Invasive and Complex: While non-surgical in terms of function, it still requires the placement of electrodes and can be time-consuming to set up.
- Limited to Motor Pathways: IONM is most effective for monitoring motor pathways and may not be useful for mapping other brain functions such as speech, memory, or sensory processing.
- Requires Specialist: The technique requires a skilled neurophysiologist to interpret the data and provide real-time feedback, making it less accessible in some settings.
- Electrode Positioning: The accuracy of the monitoring depends on the correct positioning of the electrodes, which can be challenging during surgery.

d) Near-Infrared Spectroscopy (NIRS)

Near-infrared spectroscopy (NIRS) is a non-invasive optical imaging technique used during surgery to monitor brain oxygenation and hemodynamics. NIRS works by emitting light at near-infrared wavelengths that penetrate the brain and are absorbed by different tissue types. By analyzing the reflected light, surgeons can monitor brain tissue oxygen levels and blood flow, which provides an indirect measure of brain function.

i) *How it works:*

- Sensors are placed on the patient's head to emit and detect near-infrared light.
- Changes in the absorption of light can be used to infer changes in blood oxygenation and hemodynamic activity, offering insights into brain function.

ii) *Limitations:*

- Indirect Measurement: While it can measure brain oxygenation and blood flow, it does not provide detailed information about specific brain functions such as movement or speech.
- Shallow Penetration: NIRS is effective primarily for surface brain areas and has limited ability to probe deeper structures.

iii) *Sensitivity Issues:*

The technique can be influenced by external factors like skin thickness, scalp tissue, and hair, which can affect its accuracy.

Abstract Conclusion: *Intraoperative brain mapping plays a pivotal role in modern neurosurgery, ensuring that critical brain functions are preserved while minimizing the risk of permanent damage. Current techniques, such as electrocortical stimulation, functional MRI, intraoperative neurophysiological monitoring, and near-infrared spectroscopy, offer valuable*

insights into brain activity during surgery. However, each method has its limitations, ranging from invasiveness and limited spatial resolution to the inability to monitor deep brain structures or provide real-time feedback. As the need for more precise, efficient, and less invasive mapping solutions grows, the development of new technologies and approaches becomes imperative. The next steps in neurosurgical innovation must focus on overcoming these limitations, offering real-time, comprehensive brain mapping tools that can guide surgeons with greater accuracy and ultimately improve patient outcomes.

Keywords : *Real-Time Brain Mapping, Intraoperative Brain Mapping, Neurosurgical Tools, Functional Brain Mapping, Non-Disruptive Neurosurgery, Surgical Navigation, Brain-Computer Interface, Electrophysiological Monitoring, Electrocorticography (Ecog), Functional MRI (Fmri), Neural Signal Processing, Neuroimaging Techniques, Cortical Mapping, Optical Imaging, Augmented Reality Surgery, Intraoperative Neurophysiology, Minimally Invasive, Surgical Precision, Patient Safety, Neurosurgical Workflow, Motor Cortex Mapping, Language Area Localization, Real-Time Feedback, Brain Function Preservation.*

II. INTRODUCTION

Neurosurgery is a complex and highly specialized field that requires precision and accuracy in order to successfully treat brain, spinal cord, and nervous system conditions. One of the most significant challenges in neurosurgery is the need to preserve critical brain functions while removing tumors, repairing injuries, or addressing neurological disorders. In order to achieve this, neurosurgeons must navigate the brain with extreme care, as even the slightest mistake can lead to severe, irreversible consequences for the patient. The human brain, unlike other organs, is a highly dynamic structure, with functional areas constantly interacting and shifting, further complicating surgical procedures.

One of the most essential tools for overcoming this challenge is intraoperative brain mapping, a technique that allows surgeons to identify and preserve key regions of the brain responsible for functions like speech, movement, and memory. However, traditional mapping methods often fall short in providing real-time, continuous information that is critical for effective decision-making during surgery. As a result, there has been a growing demand for advanced technologies that can offer more precise, real-time insights into brain activity, thereby improving the safety and effectiveness of neurosurgical procedures.

In this article, we will explore the mechanisms behind the existing brain mapping techniques, assess their current limitations, and propose hypothetical solutions based on emerging research and technologies. We will examine innovative strategies, such as genetically engineered tools and advanced imaging technologies, that could help overcome the current challenges and enhance neurosurgical precision. By Integrating insights from neuroscience, biomedical engineering, and real-time sensing technologies, this article aims to bridge the gap between what's currently possible and what could be achieved with the right innovations. These new strategies won't just be upgrades of existing tools — they'll be built from the ground up using concepts that have been proven in other areas of research but haven't yet been applied to intraoperative brain mapping. From the cellular mechanisms that power brain signaling to the tech behind real-time imaging, each solution we explore will be grounded in real science and pushed further to imagine what's possible.

Ultimately, the goal is to rethink the way brain mapping is done during surgery. Because for neurosurgeons, having the ability to see and understand the brain in real time — without interrupting the flow of the operation — could mean the difference between preserving a patient's ability to walk or speak... or not. And for patients facing life-altering procedures, those improvements could redefine what safe and effective brain surgery actually looks like.

III. INTEGRATING FUNCTIONAL ULTRASOUND WITH AI-POWERED SIGNAL INTERPRETATION

A promising strategy to solve the problem of disrupted or static brain mapping involves combining functional ultrasound (fUS) with AI-powered signal interpretation. Here's how this approach could work and why it holds potential:

A. What is Functional Ultrasound (fUS)?

Functional ultrasound is a relatively new imaging technique that tracks changes in cerebral blood volume — a reliable indicator of neural activity. Compared to fMRI, fUS is faster, less bulky, and more portable, making it a better candidate for intraoperative use. It can detect activity patterns in real-time and with surprisingly high resolution, making it an ideal technology for monitoring brain states during surgery.

B. How It Would Work During Surgery

Instead of using electrical stimulation to map out brain regions (which can interrupt the procedure), a neurosurgeon could place a small fUS probe over the exposed brain tissue. As the patient performs certain tasks or as natural brain activity occurs, the fUS would pick up changes in blood flow and convert that into data on active brain regions.

C. The Role of AI in Signal Translation

One of the major hurdles with fUS is interpreting the massive amount of data it collects in real time. Deep learning models trained on thousands of fUS scans could decode these patterns and generate visual heat maps highlighting critical functional areas — like those involved in speech, movement, or memory — and update them live as the brain shifts.

D. Why This Could Be Game-Changing

- No electrical stimulation needed → less invasive
- Continuous updates → adjusts in real time as the brain moves
- Visual overlays → guidance without interrupting workflow
- Adaptable hardware → more portable than fMRI, better for the OR

E. Limitations & Considerations

- Training the AI model would require massive datasets of high-quality surgical fUS recordings.
- The probe would need to be miniaturized and stabilized to fit within the surgical field without disrupting the operation.
- Surgeons would need standardized protocols for interpreting the AI's visual outputs to ensure safety.

If these challenges can be addressed, the combination of fUS and AI interpretation could be a powerful step forward — offering surgeons a real-time, dynamic, and noninvasive map of brain activity while they work.

IV. REAL-TIME ELECTROCORTICOGRAPHY (ECOG) ENHANCED BY MACHINE LEARNING PATTERN RECOGNITION

Electrocorticography (ECoG) has long been used in neurosurgery to measure electrical activity directly from the surface of the brain. However, traditional ECoG is often limited by static analysis and manual interpretation. A potential evolution of this technology could involve real-time ECoG enhanced by machine learning algorithms that can identify and interpret complex patterns in neural activity mid-surgery.

A. What is Electrocorticography (ECoG)?

ECoG involves placing electrode grids directly on the cortex to measure neural signals. It provides high temporal resolution and is especially useful for localizing seizure foci or identifying functional areas before resection. Unlike EEG, ECoG captures signals with minimal distortion and interference.

B. How It Would Work in Surgery

During brain surgery, electrode grids would be temporarily placed on exposed cortical surfaces. Instead of relying on post-processing or visual inspection alone, a machine learning model trained on functional ECoG data would analyze the signals in real-time, recognizing specific activation signatures associated with language, motor control, or other cognitive functions.

C. Machine Learning Interpretation

Deep neural networks could be trained using labeled ECoG datasets — associating wave patterns with specific brain functions. Once trained, these models would analyze live ECoG signals during surgery, flagging areas that should be preserved or avoided and updating the functional map continuously as the brain shifts.

D. Why This Could Be Game-Changing

- ECoG is already FDA-cleared and clinically familiar
- Machine learning allows for rapid, adaptive interpretation
- Could provide both broad cortical mapping and localized precision Doesn't interfere with ongoing surgery or require stimulation

E. Limitations & Considerations

- Requires large labeled datasets to train models for specific functions
- Some functional areas produce subtle or overlapping waveforms, which could confuse even trained models
- Electrode placement needs to be precise and stable to avoid shifting data mid-procedure
- Models must be interpretable and reliable, with built-in safeguards for surgical decisions

Overall, by combining ECoG's direct brain signal access with machine learning's analytical power, neurosurgeons could gain a highly precise, continuously updating brain map that responds in real-time — without halting or disrupting the surgical procedure.

V. FUNCTIONAL ULTRASOUND (FUS) WITH AI-BASED SPATIAL TRACKING SYSTEMS

Functional ultrasound (fUS) is an emerging imaging technique that measures changes in cerebral blood flow to infer neural activity. While fMRI has long been used for this purpose in research, its size, complexity, and poor intraoperative compatibility have limited its surgical use. fUS, on the other hand, is compact, fast, and can potentially be used during surgery without disrupting the operating field. Paired with AI-based spatial tracking, this technology could become a powerful real-time mapping tool.

A. What is Functional Ultrasound (fUS)?

fUS captures cerebral blood volume changes at a high spatial and temporal resolution using Doppler ultrasound principles. Neural activity increases blood flow to a region, and fUS detects this change almost instantly — serving as a proxy for brain function, similar to fMRI but with real-time capacity.

B. How It Would Work in Surgery

A small, sterile ultrasound probe would be gently placed on exposed areas of the brain. As the surgeon stimulates or manipulates different regions, the fUS device would detect local changes in blood flow. These signals would be analyzed by an AI-based tracking system that overlays functional activity onto the brain's surface in real time.

C. The Role of AI-Based Spatial Tracking

Because the brain shifts during surgery, spatial accuracy is critical. AI-enhanced systems could:

- Track the probe's position continuously
- Adjust for brain shift in real-time using surface deformation models
- Update the functional overlay to reflect live changes in anatomy and perfusion

D. Why This Could Be Game-Changing

- fUS offers real-time functional insight without disrupting tissue
- Extremely portable and cost-effective compared to MRI
- Can provide sub-millimeter resolution in localized regions
- Compatible with AI-guided overlays, helping visualize key zones

E. Limitations & Considerations

- Blood flow ≠ brain activity in every context; false positives are possible
- Requires clear acoustic windows, limiting use in deeper brain structures
- Probe pressure must be extremely gentle to avoid distorting readings
- Spatial tracking and overlay require precise calibration to avoid misalignment

Functional ultrasound, especially when combined with intelligent tracking systems, could transform intraoperative brain mapping into a dynamic, responsive process. It has the potential to give neurosurgeons a live, color-coded view of brain function — no pause, no guesswork, just real-time insight.

VI. IMPLANTABLE SMART NEURAL MESHES FOR REAL-TIME ELECTROPHYSIOLOGICAL MONITORING

An extremely innovative, though still hypothetical, approach to intraoperative brain mapping involves the temporary use of implantable smart neural meshes. These ultra-thin, flexible electronic structures would be placed directly onto the cortical surface, recording neural activity with incredible precision — all without damaging tissue or interrupting surgical workflow. This concept builds on existing research in bioresorbable electronics and stretchable sensor technology.

A. What Are Smart Neural Meshes?

These are flexible, biocompatible grids embedded with nano-scale electrodes and sensors that conform to the brain's surface. They're designed to monitor electrophysiological signals (like local field potentials or action potentials) across broad areas of the cortex in real time. Some variations, like those being tested in rodent models, can even dissolve after a certain period, removing the need for extraction.

B. How They'd Work During Surgery

Before resection or lesioning, the mesh would be gently laid onto the brain surface. As the surgery progresses, it would continuously collect electrical activity data from different regions. This data would be sent wirelessly to a processing unit that:

- Visualizes activity heatmaps in real time
- Flags areas of concern based on irregular activity
- Monitors changes as tissue is manipulated or removed

C. Why They'd Be So Effective

- Direct recording from neurons offers unmatched resolution and fidelity
- Meshes are ultra-thin and conformal, minimizing mechanical disruption
- Can cover large cortical areas, ideal for tracking functional networks
- Potential for wireless data transmission keeps surgical field uncluttered
- Could detect functional deterioration or reorganization on the fly

D. Limitations & Considerations

- Requires perfect biocompatibility to avoid triggering immune responses
- Long-term use is not practical — ideal only for intraoperative windows
- Mesh must be stably secured to prevent shifting during brain movement
- High-density data recording demands advanced real-time computing systems

If developed and translated for human use, smart neural meshes could give surgeons a live electrical map of brain activity that shifts and adapts with the surgery. It's like watching the brain speak in real time — all through an ultra-light, nearly invisible interface.

VII. CONCLUSION:

As neurosurgery continues to evolve, the demand for precision, adaptability, and real-time insight becomes more urgent than ever. The ability to map functional brain regions without disrupting surgery isn't just a technical upgrade — it's a critical shift that could redefine surgical outcomes and patient safety. Current strategies have laid a solid foundation, but they remain limited in their ability to account for the brain's dynamic and ever-changing nature.

By using existing research as a launchpad for new ideas — from optogenetics-inspired tools to adaptive AI-driven platforms and implantable smart meshes — we can start to imagine a surgical landscape where real-time functional feedback is not just possible, but seamless. While these ideas remain hypothetical, they show that the gap between what we have and what we need isn't unbridgeable. It's just waiting for the next innovation to close it.

Ultimately, this article doesn't just highlight the challenges of intraoperative brain mapping — it points toward a future where precision neurosurgery is built on tools that move and think with the brain itself.

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