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Review Article

The evolution of Electroencephalography in intraoperative neurophysiological monitoring

Asna Rahila[1], Ajith Mohan[1], A Marthanda Pillai[1], Sajeesh P[1]*

[1]Dept of Neurosciences, Ananthapuri Hospitals and Research Institute, Thiruvananthapuram, Kerala, India.

Abstract

Intraoperative neuromonitoring (IONM) has transformed surgical procedures by enabling real-time neural function monitoring and minimizing nerve injury risk. Electroencephalography (EEG) plays a critical role in IONM, providing valuable insights into cerebral cortical function during high-risk surgeries. By monitoring brain activity in real-time, EEG facilitates prompt detection of cerebral ischemia, seizures, and other neurological complications, enabling timely interventions and improved patient outcomes. EEG enables anesthesiologists to adjust anesthetic levels to maintain a desired level of sedation, preventing awareness during surgery and ensuring patient comfort. This overview of EEG in IONM covers its applications, challenges, and future directions. EEG's role in cerebral ischemia detection, anesthetic depth monitoring, and seizure identification is discussed, along with the challenges posed by anesthetic influences, artifacts, and interpretation requirements. The future of EEG in IONM is also explored, including the potential integration of artificial intelligence and advances in wireless and wearable EEG technologies.

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1. Introduction

Electroencephalography (EEG) is a neurophysiological technique that involves the study and analysis of the brain's electrical activity. By placing electrodes on the scalp or within the brain, EEG recordings capture the electrical fields generated by brain cells, providing valuable insights into brain function and activity. EEG involves free-run recordings from the scalp or surface of the brain, providing a direct measure of cortical function and activity.[1] A basic EEG setup typically requires four or more channels, with additional channels used for better localization of brain activity. The EEG signal is filtered to focus on relevant frequency bands, typically between 1-70 Hz. However, on some occasions, a wider bandwidth may be utilized to capture higher frequency components, such as gamma waves or high-frequency oscillations. Additionally, a higher sampling rate may be employed to provide a more detailed representation of brain activity patterns.[2]

EEG is a real-time measure of cortical activity, providing immediate insights into brain function. Intraoperative EEG is particularly useful for detecting widespread, gross changes in cortical function, such as those occurring during cerebral ischemia or seizure activity. Notably, intraoperative EEG does not require the high spatial resolution typically needed in diagnostic EEG studies. Instead, it focuses on detecting broad, significant changes in cortical activity. Furthermore, intraoperative EEG does not necessitate signal averaging, as it prioritizes real-time monitoring and prompt detection of critical changes in brain function.[3]

2. Techniques and Methodologies

Scalp EEG is the most commonly used method in IONM, providing a non-invasive means of monitoring cerebral cortical activity. This approach involves placing electrodes on the scalp to record EEG signals, which are then transmitted to a monitoring system for analysis. Scalp EEG

*Corresponding author: Sajeesh P
Email: psajeesh@gmail.com

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is widely used due to its ease of use, minimal setup requirements, and low risk of complications. In contrast, intracranial EEG involves placing electrodes directly on the brain surface or within the brain tissue. This approach provides higher spatial resolution and more accurate recordings of cerebral activity, but it is more invasive and typically reserved for specific surgical procedures, such as epilepsy surgery or tumor resections.[4]

EEG is highly sensitive to changes in cerebral perfusion and can provide real-time indicators of ischemic events. Under ischemic conditions, brain cells prioritize preserving their structural integrity over maintaining functional activity. As a result, changes in EEG signals can serve as an early warning system for impending ischemic changes By monitoring EEG in real-time, clinicians can quickly identify potential ischemic threats and take proactive measures to prevent them. For instance, prompt adjustments can be made to prevent hypotension or excessive brain retraction, which can exacerbate ischemic damage. This enables timely interventions to safeguard brain function and minimize potential damage. Cerebral ischemia, a major concern in surgeries involving major blood vessels, can lead to postoperative neurological deficits if not detected early. EEG can detect ischemic patterns characterized by decreased amplitude of fast-wave activity, increased slow-wave activity (theta and delta waves), and unilateral attenuation in regions with compromised blood flow.[5]

Raw EEG patterns can also be used to assess depth of anesthesia. The following patterns are commonly observed: awake pattern, characterized by high-frequency activity (beta waves) with low amplitude; sedation pattern, characterized by slowing of background rhythm (alpha waves) with increased amplitude; anesthesia pattern, characterized by further slowing of background rhythm (theta and delta waves) with increased amplitude; and burst suppression pattern, characterized by periodic bursts of high-amplitude activity separated by periods of low-amplitude activity (**Figure 1**)

To better understand the raw EEG signal, it is processed into frequency spectra, providing a graphical representation of brain activity across different frequency ranges. This is achieved through Fourier analysis, which decomposes the raw EEG signal into its constituent frequencies. The resulting frequency spectra are then plotted and updated in real-time, allowing clinicians to monitor changes in brain activity over time. Several formats are used to display these spectra, including Compressed Spectral Array (CSA), which provides a condensed representation of the frequency spectrum. The Density Spectral Array offers a graphical display of the frequency spectrum, showing the distribution of power across different frequencies. Additionally, the Spectral Edge is calculated, representing the frequency below which a certain percentage (e.g., 95%) of the signal's power is contained. Symmetry is also measured, indicating the balance between different frequency components, which can signal changes in brain activity. These graphical representations enable clinicians to quickly identify changes in brain activity and make informed decisions during surgical procedures.[6]

EEG-derived indices such as the Bispectral Index (BIS) and Patient State Index (PSI) provide quantitative assessments of anesthetic depth. Maintaining an appropriate depth of anesthesia is crucial in preventing intraoperative awareness while avoiding excessive sedation, which can prolong recovery and increase complications. A BIS score of 40–60 generally indicates adequate anesthesia, while lower scores may suggest excessive anesthesia, and higher scores may indicate insufficient anesthesia.[7]

2.1. Clinical applications

An ischemic EEG event occurs when there is an attenuation of the raw EEG signal by more than one-third of the baseline value, sustained for 30 seconds or longer. Additionally, a decrease in spectral edge frequency of 50% or more, lasting for more than 10 minutes, is also indicative of an ischemic EEG event.[8] Intraoperative EEG monitoring is employed to detect cerebral ischemia secondary to carotid cross-clamping during carotid endarterectomy (CEA) and other surgical procedures. During carotid surgery, a 50% decrease in overall EEG amplitude may indicate the need for carotid shunting. Alternatively, a 50% reduction in alpha and beta activity or a doubling of low-frequency activity may also necessitate shunting to prevent ischemic injury (**Figure 2**). On the other hand, patients with normal EEG readings may be able to avoid shunting, thereby reducing the risk of iatrogenic complications associated with shunt placement. Typically, any clamp-related EEG changes occur within 1 minute of carotid cross-clamping, allowing for prompt identification and intervention.[9]

In cardiovascular and thoracic surgeries, particularly those involving deep hypothermic circulatory arrest (DHCA), EEG plays a crucial role as a "brain thermometer". EEG monitoring helps assess the degree of hypothermia and determines when adequate cooling has been achieved, typically after at least 3 minutes. Adequate cooling is confirmed when no discernible activity is visible on the EEG, indicating that the brain has reached a sufficient level of hypothermia to safely undergo circulatory arrest.[10]

EEG enables early detection of epileptiform activity, allowing the surgical team to take preventive measures. Certain neurosurgical procedures, such as epilepsy surgery or tumor resections, carry a risk of triggering intraoperative seizures. Focal spikes or sharp waves may indicate seizure onset, while continuous high-frequency oscillations suggest hyper excitability in cortical regions.[11]

EEG plays a crucial role in epilepsy surgery by aiding in the localization of epileptogenic zones and guiding surgical interventions. Two key invasive EEG modalities, electrocorticography (ECoG) and stereo electroencephalography (sEEG), provide high-resolution mapping of seizure activity (**Figure 3**). ECoG, performed with subdural grid and strip electrodes, allows real-time assessment of cortical excitability during surgery, ensuring precise resection while minimizing damage to functional areas.[12] sEEG, using depth electrodes implanted in three-dimensional trajectories, is particularly useful for identifying deep-seated epileptic foci and network-based epilepsies. Specialized electrodes, including hybrid depth electrodes with micro-contacts enhance diagnostic accuracy and therapeutic monitoring.[13] These advanced EEG techniques have significantly improved surgical outcomes, increasing the likelihood of seizure freedom while preserving neurological function.

3. Challenges and Limitations of EEG in IONM

EEG signal processing and interpretation require expertise in neurophysiology and signal analysis. Clinicians must be able to recognize normal and abnormal EEG patterns, identify artifacts and noise, and adjust treatment strategies based on EEG findings. One of the significant challenges of using EEG in IONM is the influence of anesthetic agents on EEG signals. Different anesthetic agents can alter EEG patterns, sometimes mimicking ischemic or epileptic changes. For example, certain anesthetics can cause a decrease in EEG amplitude, which may be misinterpreted as a sign of cerebral ischemia. Conversely, other anesthetics can increase EEG activity, potentially masking signs of cerebral dysfunction. Therefore, it is essential to consider the effects of anesthetic agents when interpreting EEG signals in the operating room.[14]

Another challenge of EEG in IONM is its susceptibility to artifacts. EEG signals are prone to contamination from electrical interference, muscle activity, and movement artifacts. Electrical interference from surgical equipment, such as electrocautery, can cause significant artifacts in EEG signals. Muscle activity, particularly in the scalp and facial muscles, can also contaminate EEG signals. Movement artifacts, caused by patient movement or surgical manipulation, can further compromise EEG signal quality. To minimize these artifacts, EEG electrodes must be carefully placed and secured, and electrical interference must be minimized. Electrode impedance should be checked periodically to ensure optimal signal quality and accuracy.[15]

Accurate EEG interpretation requires expertise in neurophysiology, which may not always be available in all surgical centers. EEG interpretation is a complex process that requires a thorough understanding of normal and abnormal EEG patterns, as well as the effects of anesthetic agents and surgical procedures on EEG signals. Inexperienced clinicians may misinterpret EEG signals, potentially leading to incorrect diagnoses or inappropriate treatment. Therefore, it is essential to have experienced clinicians trained in EEG interpretation available in the operating room to ensure accurate and effective IONM.[16]

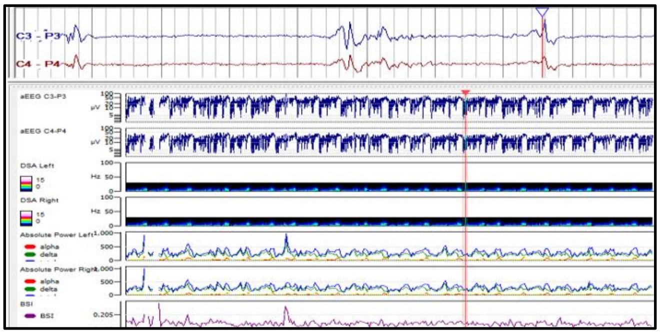

Figure 1: EEG showing burst-suppression pattern.

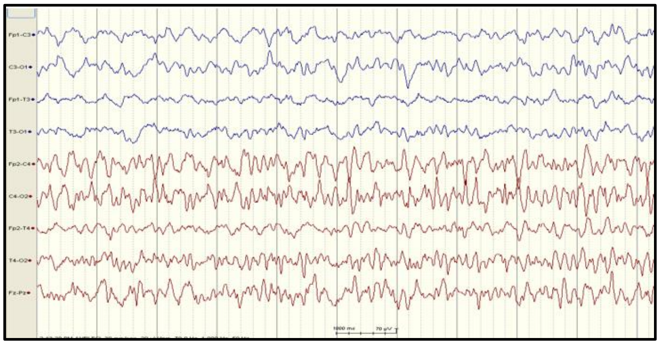

Figure 2: Cerebral ischemia secondary to carotid cross clamping during CEA, left hemisphere EEG showing 50% loss of alpha and beta activity/ doubling of low-frequency activity.

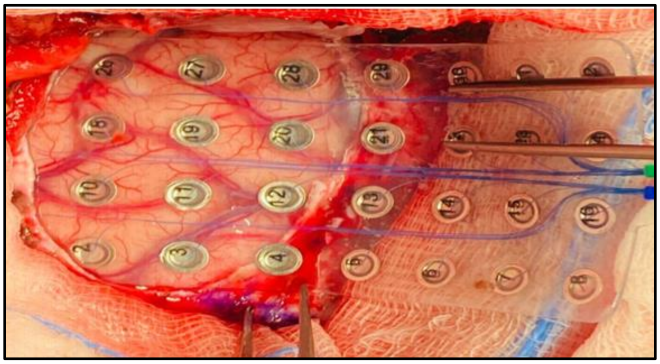

Figure 3: Placement of a grid electrode for acute electro corticography (ECoG) recording in epilepsy surgery

The lack of standardization in EEG protocols and guidelines is another challenge facing EEG in IONM. Different institutions and clinicians may use varying EEG protocols, making it challenging to compare results and ensure consistency. Standardized EEG protocols and guidelines would help to ensure that EEG is used consistently and effectively in IONM, ultimately improving patient outcomes.[17]

EEG has several limitations, including an inability to detect subcortical injury. Additionally, EEG has a high false-positive rate, largely due to its sensitivity to anesthesia and medications. EEG sensitivity is also diminished in patients with a history of stroke. To overcome these limitations and improve detection of deep brain and brainstem ischemia, evoked potentials (EPs) can be used in conjunction with EEG. Somatosensory evoked potentials (SEPs) are particularly useful, as they can evaluate deep brain and brainstem structures. Multi-modality intraoperative neuromonitoring (IONM) provides a comprehensive approach to monitoring neural function during surgery, offering a more accurate and reliable assessment of the patient's neurological status.[18]

Finally, the cost and accessibility of EEG equipment and expertise can be a significant challenge in some institutions. EEG equipment can be expensive, and the cost of maintaining and upgrading equipment can be prohibitive for some institutions. Furthermore, accessing experienced clinicians trained in EEG interpretation can be challenging, particularly in rural or resource-constrained areas.[19]

4. Future Directions and Innovations

The field of EEG in IONM is rapidly evolving, with several promising innovations on the horizon. One of the most exciting developments is the integration of Artificial Intelligence (AI) in EEG analysis. AI-driven EEG interpretation has the potential to significantly improve ischemia and seizure detection accuracy. By leveraging machine learning algorithms and large datasets, AI can identify complex patterns in EEG signals that may not be apparent to human interpreters. This could enable earlier detection of cerebral ischemia and seizures, allowing for more timely interventions and improved patient outcomes.[20]

Modern EEG systems use advanced algorithms to filter noise, detect significant pattern changes, and provide automated alerts for ischemia or seizures. These systems can also integrate data from multiple EEG channels, providing a comprehensive view of cerebral activity. The use of advanced signal processing algorithms and automated analysis tools has improved the accuracy and reliability of EEG monitoring in IONM.[21]

Another promising area of innovation is the integration of EEG with other IONM modalities, such as somatosensory evoked potentials (SSEPs) or motor evoked potentials (MEPs). Multimodal IONM integration has the potential to enhance intraoperative neurological assessment by providing a more comprehensive understanding of cerebral function. By combining EEG with other modalities, clinicians can gain a more nuanced understanding of cerebral activity and identify potential issues earlier. This could enable more effective interventions and improved patient outcomes.[22]

Advances in wireless EEG technology are also expected to transform the field of IONM. Wireless and wearable EEG systems could significantly improve ease of use and reduce setup time in the operating room. These systems would enable clinicians to quickly and easily establish EEG monitoring, even in complex or emergency situations. Additionally, wireless EEG systems could enable more flexible and dynamic monitoring, allowing clinicians to adjust their approach as needed. Another area of innovation is the development of dry electrode technologies, which could further simplify EEG setup and reduce preparation time.[23]

The integration of EEG with other technologies, such as functional near-infrared spectroscopy (fNIRS) or transcranial Doppler ultrasonography (TCD), is also an area of active research. These multimodal approaches could provide a more comprehensive understanding of cerebral function and enable more effective interventions.[24] Finally, the development of more advanced signal processing algorithms and machine learning techniques is expected to further improve EEG analysis and interpretation. These advances could enable more accurate and reliable detection of cerebral ischemia and seizures, as well as more effective monitoring of anesthetic depth and cerebral function.

5. Conclusion

EEG is a vital component of intraoperative neuromonitoring, offering critical insights into cerebral function during high-risk surgeries. Its applications in ischemia detection, anesthesia monitoring, and seizure detection make it an essential tool for enhancing surgical safety. However, challenges such as anesthetic interference, technical artifacts, and interpretation complexities must be addressed to maximize its effectiveness. Future advancements in AI, multimodal monitoring, and EEG signal processing are expected to improve the accuracy and reliability of EEG in IONM, ultimately benefiting patient outcomes. Intraoperative EEG monitoring is a vital tool, and raw EEG signals should be prioritized to ensure accurate interpretation. The choice of EEG montage may need to be tailored to the specific surgical procedure. A multimodal approach, combining EEG with other modalities, is recommended for comprehensive monitoring.

6. Source of Funding

None.

7. Conflict of Interest

None.

References

1. Cohen MX. Where does EEG come from and what does it mean?. *Trends in Neurosci.* 2017;40(4):208-18.
2. Noorlag L, van Klink NE, Kobayashi K, Gotman J, Braun KP, Zijlmans M. High-frequency oscillations in scalp EEG: a systematic review of methodological choices and clinical findings. *Clin Neurophysiol.* 2022;137:46-58.

3. Yuan I, Bong CL, Chao JY. Intraoperative pediatric electroencephalography monitoring: an updated review. *Korean J Anesthesiol*. 2024;77(3):289-305.
4. Ramantani G, Maillard L, Koessler L. Correlation of invasive EEG and scalp EEG. *Seizure*. 2016;41:196-200.
5. Gaspard N. Current clinical evidence supporting the use of continuous EEG monitoring for delayed cerebral ischemia detection. *J Clin Neurophysiol*. 2016;33(3):211-6.
6. LaRoche SM, Haider HA, editors. Handbook of ICU EEG monitoring. Springer Publishing Company; 2018;28.
7. Schneider G, Mappes A, Neissendorfer T, Schabacker M, Kuppe H, Kochs E. EEG-based indices of anaesthesia: correlation between bispectral index and patient state index?. *Eur J Anaesthesiol*. 2004;21(1):6-12.
8. Kamitaki BK, Tu B, Wong S, Mendiratta A, Choi H. Quantitative EEG changes correlate with post-clamp ischemia during carotid endarterectomy. *J Clin Neurophysiol*. 2021;38(3):213-20.
9. Simon MV, Malcharek M, Ulkatan S. Monitoring in carotid endarterectomy. *Clin Neurol*. 2022;186:355-74.
10. Alkhatip, A.A.A.M.M., Kamel, M.G., Farag, E.M., Elayashy, M., Farag, A., Yassin, H.M., Bahr, M.H., Abdelhaq, M., Sallam, A., Kamal, A.M. and El Emady, M.F. Deep hypothermic circulatory arrest in the pediatric population undergoing cardiac surgery with electroencephalography monitoring: a systematic review and meta-analysis. *J Cardiothoracic Vascular Anesthesia*, 2021;35(10):2875-88.
11. Jayakar P, Gotman J, Harvey AS, Palmini A, Tassi L, Schomer D, Dubeau F, Bartolomei F, Yu A, Kršek P, Velis D. Diagnostic utility of invasive EEG for epilepsy surgery: indications, modalities, and techniques. *Epilepsia*. 2016;57(11):1735-47.
12. Goel K, Pek V, Shlobin NA, Chen JS, Wang A, Ibrahim GM, Hadjinicolaou A, Roessler K, Dudley RW, Nguyen DK, El-Tahry R. Clinical utility of intraoperative electrocorticography for epilepsy surgery: a systematic review and meta-analysis. *Epilepsia*. 2023;64(2):253-65.
13. Samanta D. Recent developments in stereo electroencephalography monitoring for epilepsy surgery. *Epilepsy Behav*. 2022;135:108914.
14. Hagihira S. Changes in the electroencephalogram during anaesthesia and their physiological basis. *Brit J Anaesthesia*. 2015;115(1):27-31.
15. Tatum WO, Dworetzky BA, Schomer DL. Artifact and recording concepts in EEG. *J Clin Neurophysiol*. 2011;28(3):252-63.
16. Greenblatt AS, Beniczky S, Nascimento FA. Pitfalls in scalp EEG: Current obstacles and future directions. *Epilepsy Behavior*. 2023;149:109500.
17. Sinha SR, Sullivan LR, Sabau D, Orta DS, Dombrowski KE, Halford JJ, Hani AJ, Drislane FW, Stecker MM. American clinical neurophysiology society guideline 1: minimum technical requirements for performing clinical electroencephalography. *Neurodiagnostic J*. 2016;56(4):235-44.
18. Bozzani A, Arici V, Ticozzelli G, Pregnolato S, Boschini S, Fellegara R, Carando S, Ragni F, Sterpetti AV. Intraoperative cerebral monitoring during carotid surgery: a narrative review. *Ann Vascul Surge*. 2022;78:36-44.
19. Radhakrishnan K. Challenges in the management of epilepsy in resource-poor countries. *Nat Rev Neurol.* 2009;5(6):323-30.
20. Tavares D, Lopes AI, Castro C, Maia G, Leite L, Quintas M. The intersection of artificial intelligence, telemedicine, and neurophysiology: opportunities and challenges. Handbook of Research on Instructional Technologies in Health Education and Allied Disciplines. 2023:130-52.
21. Tatum IV WO. Handbook of EEG interpretation. Springer Publishing Company; 2021 May 7.
22. Wong AK, Shils JL, Sani SB, Byrne RW. Intraoperative neuromonitoring. *Neurol Clin.* 2022;40(2):375-89.
23. Hinrichs H, Scholz M, Baum AK, Kam JW, Knight RT, Heinze HJ. Comparison between a wireless dry electrode EEG system with a conventional wired wet electrode EEG system for clinical applications. *Scient Rep.* 2020;10(1):5218.
24. Chiarelli AM, Zappasodi F, Di Pompeo F, Merla A. Simultaneous functional near-infrared spectroscopy and electroencephalography for monitoring of human brain activity and oxygenation: a review. *Neurophotonics.* 2017;4(4):041411.

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