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IP Indian Journal of Neurosciences

Journal homepage: https://www.ijnonline.org/

Review Article

Advancements in remote EEG monitoring: Technology, applications, and future directions

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Abstract

The integration of remote electroencephalogram (EEG) monitoring into neurological care has revolutionized the management of brain-related conditions, facilitating real-time, continuous monitoring in diverse clinical settings such as routine EEG, Ambulatory Video EEG Monitoring, Intensive Care Unit EEG monitoring, and epilepsy monitoring units. Remote EEG allows for quicker diagnosis and timely treatment decisions by significantly reducing turnaround time for EEG reports. In ICUs, remote EEG facilitates the early detection of conditions such as non-convulsive seizures and status epilepticus, providing critical insights into the neurological status of critically ill patients. Ambulatory Video EEG Monitoring enhances chronic disease management, particularly in epilepsy, by monitoring seizure frequency and triggers, enabling long-term, patient-centered care from home. Technological advancements in portable EEG devices, cloud-based platforms, and Artificial Intelligence (AI) integration have enabled real-time data analysis, improving diagnostic accuracy and treatment outcomes. The expanding field of remote EEG is creating new job opportunities across healthcare, technology, and research sectors. However, the widespread adoption of remote EEG necessitates international guidelines and certifications to ensure equipment accuracy, data security, and patient safety. Future innovations in wearable devices, AI algorithms, and the global expansion of telemedicine will further transform the landscape of remote EEG monitoring, improving healthcare access and patient outcomes, especially in underserved regions. As the technology advances, regulatory measures must prioritize the security of patient data, ensuring compliance with healthcare data protection standards.

Keywords: Electroencephalography, Remote EEG, Ambulatory EEG

Received: 01-02-2025; **Accepted:** 03-08-2025; **Available Online**: 14-04-2025

1. Introduction

The advent of remote electroencephalogram (EEG) monitoring has transformed neurological care by enabling real-time monitoring of brain activity across diverse settings.[1] The concept of remote EEG, or tele-EEG, emerged in the 1960s with telephone-based transmission systems, but was limited by poor signal quality. Digital EEG improved recordings, analysis, and transmission, paving the way for remote EEG monitoring. With the rise of the internet, cloud computing, and mobile devices, remote EEG has become popular in settings like epilepsy monitoring, sleep disorders diagnosis, neurocritical care, and clinical trials. Advances in technology have led to portable, wireless, and dry EEG sensors, making remote EEG more accessible and convenient.[2] In routine EEG, remote monitoring enables patients to receive immediate EEG reports with a significantly reduced turnaround time, allowing for quicker diagnosis and more timely treatment decisions.[3] In epilepsy monitoring units, remote EEG allows for continuous surveillance of patients' brain activity over extended periods, enabling clinicians to track seizure activity, identify triggers, and adjust treatment plans promptly, all without the need for extended hospital stays.[4] This approach not only enhances patient comfort but also optimizes resource utilization in busy hospital environments. Similarly, in ICUs, remote EEG monitoring provides crucial insights into patients neurological status, especially for critically ill or comatose patients, allowing for real-time detection of conditions such as non-convulsive seizures and status epilepticus.[5] Ambulatory video EEG monitoring (AVEM) monitoring has garnered increasing importance in modern healthcare due to its ability to facilitate real-time, long-term brain activity monitoring outside traditional clinical settings.[6] This is

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http://doi.org/10.18231/j.ijn.2025.002

particularly valuable in the context of chronic neurological conditions, where continuous monitoring is often required for accurate diagnosis and management. The ability to monitor patients remotely significantly reduces the burden on healthcare systems, allowing for more personalized care, early intervention, and increased access to healthcare in underserved populations.[7]

Chronic disease management can be significantly enhanced through continuous AVEM, particularly for conditions like epilepsy, where seizure frequency and triggers can be accurately tracked over extended periods, eliminating the need for repeated hospital visits. Ambulatory EEG devices and remote EEG monitoring enables patient centered care by allowing patients to remain in the comfort of their own homes while being monitored, thereby improving compliance and overall comfort. Remote EEG monitoring has emerged as a crucial breakthrough, enabling data collection outside clinical environments, such as patients' homes or during daily activities. This innovation is particularly vital for patients with epilepsy, sleep disorders, neurological conditions, and mental health issues, who require frequent monitoring without necessitating hospitalization. Remote EEG monitoring fills a critical gap in resource-constrained settings by providing immediate access to expert clinical interpretation, despite limited availability of specialized professionals such as EEG interpreters, clinical neurophysiologists, epileptologists, and neurologists.[8] Through remote EEG monitoring, experts from around the world can provide timely and accurate reports, enabling healthcare professionals to develop effective treatment strategies and improve patient outcomes. The integration of remote EEG monitoring with telemedicine has transformed the healthcare landscape, providing vital access to healthcare services for patients in rural or underserved regions worldwide.[9]

1.1. Ambulatory video EEG remote monitoring

AVEM offers numerous benefits, particularly for patients requiring long-term surveillance of brain activity, by providing convenience, cost-effectiveness, longitudinal monitoring, and real-time intervention.[10] Patients can undergo remote EEG monitoring in their everyday environments, allowing for a more natural assessment of their neurological status and enhancing the accuracy of diagnosis. Remote EEG monitoring reduces hospital admissions and in-person visits, resulting in lower overall healthcare costs while maintaining high-quality care. The longitudinal monitoring capability of remote EEG enables the tracking of brain activity over extended periods, facilitating the detection of slowly evolving conditions such as epilepsy, sleep disorders, and neurodegenerative diseases. Remote EEG monitoring allows clinicians to intervene promptly when abnormal activity is detected, providing a significant advantage in conditions like epilepsy, where early intervention can prevent harm and improve patient outcomes.[11]

1.2. Technology and infrastructure for remote EEG monitoring

Remote EEG monitoring relies heavily on technological advancements to ensure accurate and real-time data collection, analysis, and transmission, which is facilitated by portable EEG devices, cloud-based platforms, and Artificial Intelligence (AI) integration.[12,13] Modern portable EEG devices have revolutionized the field of remote EEG monitoring by providing lightweight, comfortable, and easy-to-use systems that enable continuous, long-term monitoring without impeding the patient's daily life . These devices include EEG headbands, caps, and wristbands equipped with dry or saline electrodes that facilitate high-quality data collection. Cloud-based platforms play a critical role in remote EEG monitoring by providing secure data storage and remote access by clinicians, enabling real-time monitoring and timely intervention. [12,13] Moreover, cloud-based platforms facilitate the integration of AI and machine learning algorithms that automate the detection and analysis of abnormalities, such as seizures or sleep disruptions, from raw EEG data (**Figure 1**). The integration of AI and machine learning algorithms in remote EEG monitoring enables predictive analytics, which is a significant step towards personalized treatment plans. By leveraging AI-driven insights, clinicians can develop more effective treatment strategies tailored to individual patient needs.[13] The role of AI in remote EEG is crucial for enhancing accuracy, efficiency, and accessibility. AI-powered algorithms analyze vast amounts of EEG data in real-time, identifying patterns and anomalies with precision. AI automates data processing and reporting, improving diagnostic accuracy and reducing false positives. The integration of AI with remote EEG enables personalized treatment plans and monitoring. AI-powered remote EEG expands access to neurological care, especially in underserved areas. [12,13]

1.3. Clinical applications of remote EEG monitoring

Remote EEG monitoring provides significant clinical value across a range of neurological and psychological conditions, offering essential data for diagnosis, treatment, and management. In epilepsy management, continuous remote EEG monitoring is particularly valuable, enabling real-time seizure detection, seizure pattern identification, seizure trigger identification, and seizure frequency monitoring. Promptly identifying seizures allows clinicians to adjust medication regimens and improve patient outcomes. Remote EEG monitoring facilitates the recognition of seizure patterns, enabling clinicians to develop more effective treatment plans. Remote EEG monitoring enables clinicians to track seizure frequency, allowing for timely adjustments to treatment plans. This technology has also improved the accuracy of seizure diagnoses, reducing the risk of misdiagnosis and improving patient outcomes.[10]

In intensive care units (ICUs), continuous EEG monitoring is crucial for detecting seizures and status

epilepticus in critically ill patients. Remote EEG monitoring enables clinicians to monitor patients in real-time, facilitating prompt interventions and improving patient outcomes.[5] ICU EEG monitoring also enables clinicians to monitor patients with acute brain injuries, such as traumatic brain injuries or stroke. Remote EEG monitoring has improved the care of critically ill patients, enabling clinicians to make more informed decisions and improving patient outcomes. The use of remote monitoring EEG has revolutionized the diagnosis and management of non-convulsive status epilepticus (NCSE) and other specific EEG patterns in ICU patients. Remote EEG monitoring enables clinicians to detect epileptiform abnormalities, non-convulsive seizures, NCSE and other conditions in real-time, facilitating prompt interventions and improving patient outcomes. (**Figure 2**)

An Epilepsy Monitoring Unit (EMU) is a specialized facility designed to evaluate patients with epilepsy who are candidates for surgery. Remote EEG monitoring plays a critical role in EMUs, enabling clinicians to monitor patients' seizure activity in real-time. By analyzing EEG data, clinicians can identify seizure patterns, seizure triggers, and seizure frequency, providing valuable insights for surgical planning. Remote EEG monitoring also enables clinicians to assess the effectiveness of surgical interventions and make adjustments to treatment plans as needed. EMUs equipped with remote EEG monitoring technology can improve patient outcomes and enhance the overall quality of care.[4]

Ambulatory EEG monitoring involves using portable EEG devices to monitor patients' seizure activity in their daily lives. Remote EEG monitoring enables clinicians to receive real-time data from these devices, facilitating prompt interventions and improving patient outcomes. By leveraging ambulatory EEG monitoring, clinicians can gain valuable insights into seizure patterns, seizure triggers, and seizure frequency, enabling more accurate diagnoses and personalized treatment plans. Remote EEG monitoring also enhances patient convenience, reducing the need for prolonged hospital stays and enabling patients to undergo monitoring in the comfort of their own homes or office. Ambulatory EEG monitoring can also improve patient engagement, empowering individuals to take a more active role in their care and improving overall quality of life.[10,11]

2.4. Job opportunities in remote EEG monitoring

As the field of remote EEG monitoring continues to expand, it creates new and exciting job opportunities across various sectors, including healthcare, technology, and research. Clinical Neurophysiologists play a vital role in remote EEG monitoring, as they interpret EEG data remotely, providing critical support for clinical decisions and patient care.[14,15] These professionals must possess expertise in EEG interpretation, as well as excellent communication skills to collaborate with healthcare teams and patients. The integration of machine learning and AI in EEG data analysis has created a growing demand for Data Analysts and AI Specialists. These specialists design, develop, optimize, and implement algorithms to automate seizure detection, diagnose neurological conditions, and predict patient outcomes. Their expertise in AI, machine learning, and data analytics is crucial for advancing remote EEG monitoring. Telehealth Technologists are essential for setting up and managing remote EEG systems, ensuring seamless connectivity and data transmission.[15,16] As telemedicine adoption increases, the demand for skilled Telehealth Technologist will continue to grow. These technologist must possess technical expertise, as well as excellent patient communication skills. Additional job opportunities in remote EEG monitoring include EEG Technologistsresponsible for preparing patients for EEG recordings, setting up equipment, and ensuring high-quality data collection. EEG technologists also play a vital role in refining and editing EEG data, preparing comprehensive EEG reports, and assisting clinical neurophysiologists and neurologists in interpreting EEG results to support accurate diagnosis and treatment. Medical Device Specialists who develop, test, and market remote EEG monitoring devices, ensuring compliance with regulatory requirements.[17]

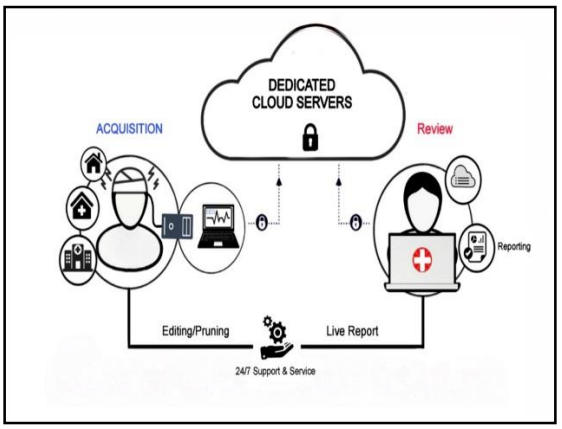

Figure 1: Workflow of remote EEG monitoring

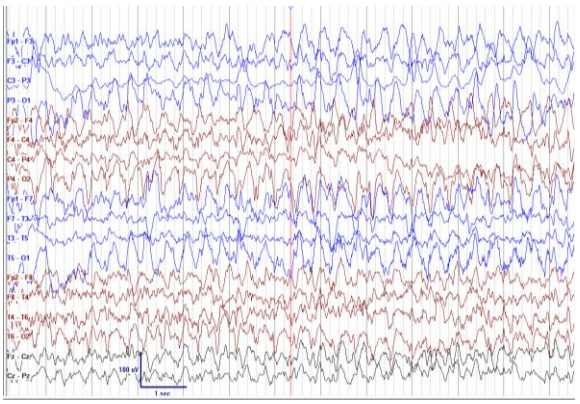

Figure 2: Remote monitoring of ICU patient showing rhythmic generalized spikes with an evolution in frequency.

2.5. Need for international certification and guidelines

As remote EEG monitoring becomes more widespread, standardization of equipment and protocols is critical. International certification bodies, such as the International Federation of Clinical Neurophysiology and the American Clinical Neurophysiology Society (ACNS), are working to establish guidelines that ensure the accuracy and safety of remote monitoring systems.[18] These standards will help mitigate issues like data security, signal interference, and misinterpretation, which could lead to false diagnoses or delayed treatments.The growing adoption of remote EEG systems underscores the need for international standards and guidelines to ensure device quality, data accuracy, and patient safety. Regulatory bodies, such as the US Food and Drug Administration (FDA) and the European Medicines Agency (EMA), play a crucial role in developing frameworks for certifying remote EEG devices. These frameworks must guarantee that remote EEG devices meet necessary technical and safety standards, including device accuracy and reliability, data security and privacy, electromagnetic compatibility, patient safety, and clinical validation.[19]

To ensure the safety and efficacy of remote EEG devices, regulatory bodies should collaborate with industry stakeholders, establish clear certification processes, conduct regular audits and inspections, and provide education and training. By establishing and enforcing international standards and guidelines, regulatory bodies can ensure that remote EEG systems provide high-quality, accurate, and safe monitoring for patients worldwide. The development of international standards and guidelines for remote EEG devices is essential for promoting innovation, improving patient outcomes, and enhancing the overall quality of neurological care.[20]

The certification process for remote EEG devices should be transparent, efficient, and based on rigorous scientific evidence. Regulatory bodies should also provide guidance on the labeling and marketing of remote EEG devices, ensuring that manufacturers accurately convey the benefits, risks, and limitations of these devices. Furthermore, regulatory bodies should establish mechanisms for reporting and addressing adverse events related to remote EEG devices, ensuring that patient safety is prioritized.[21]

2.6. Future directions of remote EEG monitoring

The future of remote EEG monitoring is promising, with several anticipated innovations that will revolutionize the field of neurological care. Next-generation wearables will likely play a significant role in shaping the future of remote EEG monitoring, with devices becoming even more compact, comfortable, and integrated with other wearable health technologies, such as fitness trackers.[22] These advancements will enable seamless monitoring of brain activity in daily life, providing valuable insights into neurological function and facilitating early intervention. The integration of remote EEG monitoring with neurofeedback therapies will also be an area of significant growth, with applications in mental health, cognitive enhancement, and rehabilitation. Neurofeedback therapies have shown promise in improving cognitive function, reducing symptoms of anxiety and depression, and enhancing overall brain health. By combining remote EEG monitoring with neurofeedback therapies, clinicians will be able to provide more personalized and effective treatment plans.[23]

The global expansion of telemedicine will also drive innovations in remote EEG monitoring, particularly in low-cost, portable devices that can benefit populations in developing countries. As more regions embrace telemedicine and digital health, the demand for remote EEG monitoring will increase, leading to the development of more affordable and accessible devices. This, in turn, will improve healthcare outcomes for millions of people worldwide, particularly those with limited access to specialized neurological care.[24]

Furthermore, advancements in artificial intelligence and machine learning will enable the development of more sophisticated algorithms for analyzing EEG data, leading to improved diagnostic accuracy and personalized treatment plans. The future of remote EEG monitoring is indeed promising, with numerous innovations on the horizon that will transform the field of neurological care. The Health Insurance Portability and Accountability Act (HIPAA), along with other international patient data transfer regulations in each country, must ensure the proper handling and security of remote EEG cloud-based data to protect patient privacy and maintain compliance with healthcare data protection standards during remote EEG monitoring.[25]

2. Conclusion

Remote EEG monitoring is revolutionizing the field of neurology by enabling continuous, real-time monitoring of brain activity outside traditional clinical settings, offering significant benefits such as improved diagnostic accuracy, personalized care, and reduced healthcare costs. With advancements in portable EEG devices, cloud-based platforms, and artificial intelligence, this technology is enhancing the management of neurological conditions like epilepsy, sleep disorders, and neurodegenerative diseases. The growing demand for remote monitoring is creating new job opportunities across healthcare and technology sectors. However, ensuring the safety, accuracy, and data privacy of these systems requires robust international standards and certification. As telemedicine expands globally, remote EEG monitoring promises to bridge gaps in healthcare access, improving outcomes for patients worldwide while shaping the future of personalized and accessible neurological care.

3. Source of Funding

None.

4. Conflict of Interest

None.

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Cite this article Dev JS, Nair AS, Anilkumar TV, Pillai AM, Parameswaran S. Advancements in remote EEG monitoring: Technology, applications, and future directions. *IP Indian J Neurosci* 2025;11(1):3-7.