ACCSCIENCE PUBLISHING

Advanced Neurology

REVIEW ARTICLE

Artificial intelligence in epilepsy education

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Abstract

The emergence of artificial intelligence (AI) has revolutionized the landscape of epilepsy education and management by providing innovative solutions to the challenges of diagnosis, treatment, and patient care. This review evaluates the multifaceted role of AI in epilepsy, focusing on its impact on early diagnosis, seizure prediction, and the development of personalized treatment plans. AI tools, including machine learning algorithms and neural networks, have demonstrated significant promise in enhancing diagnostic accuracy and identifying epileptic patterns. This study explores various AI-driven educational platforms designed to improve the knowledge and skills of healthcare professionals, patients, and caregivers in managing epilepsy. Moreover, AI applications in wearable devices and mobile health platforms facilitate real-time monitoring and patient engagement, ultimately improving quality of life. However, integrating AI into clinical practice presents several challenges, including the need for large and high-quality datasets, interdisciplinary collaboration, data privacy, and ethical considerations. This review highlights these barriers while suggesting uniform protocols and frameworks for efficiently translating AI technologies into clinical practice. It underscores AI's transformative potential in epilepsy care and education, advocating for ongoing research and collaborative efforts among technologists, clinicians, and educators, while emphasizing the importance of user-friendly design, regular assessments, and ethical considerations to maximize AI's impact in this critical field.

Keywords: Epilepsy education; Artificial intelligence; Epilepsy

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Citation: Otu W, Khan MU, Javed HT, Sheikh IS. Artificial intelligence in epilepsy education. *Adv Neurol*. 2025;4(3):16-28. doi: 10.36922/an.4777

Received: September 5, 2024

1st revised: November 3, 2024

2nd revised: December 18, 2024

3rd revised: January 10, 2025

Accepted: January 15, 2025

Published online: February 4, 2025

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1. Introduction

Epilepsy is a neurological disorder characterized by unprovoked, recurrent seizures stemming from abnormal electrical activity in the brain.[1] Affecting millions globally, epilepsy arises from a complex interplay of genetic and environmental factors that disrupt the balance between excitatory and inhibitory brain signals, leading to hyperexcitability

and seizure activity.[2] With diverse manifestations across patients, diagnosing and managing epilepsy poses unique challenges, often requiring specialized approaches for personalized treatment.[1,2]

In the United States, approximately 3.4 million individuals are affected by epilepsy, with 150,000 new cases diagnosed annually.[3] This condition spans all ages, from children to older adults, and imposes significant medical, emotional, social, and financial challenges for patients and their families.[4] Major risk factors include traumatic brain injury, genetic predispositions, neurodevelopmental issues, stroke, and central nervous system infections.[5] Diagnosis commonly involves reviewing medical history, conducting physical exams, performing neuroimaging, and primarily utilizing electroencephalography (EEG) to assess brain activity.[6] However, accurately interpreting EEG data requires advanced expertise, creating barriers to timely diagnosis. While genetic testing can provide insights in specific cases, its accessibility and cost remain limiting factors.[7]

Artificial intelligence (AI) is increasingly advancing epilepsy care by automating EEG analysis, detecting subtle seizure patterns, and facilitating faster, more accurate diagnoses, especially in settings with limited specialized expertise.[8] AI-driven tools also have the potential to predict seizure patterns, enabling patients to take proactive safety measures.[9] In addition, AI-powered applications, wearable devices, and telehealth services are revolutionizing epilepsy care by improving access to personalized support tailored to individual needs.[10]

This study explores how AI implementation can enhance epilepsy education by improving EEG interpretation skills, supporting patient self-management, and creating innovative learning pathways for neuro physicians while highlighting the collaborative efforts of multiple institutions in this field. Moreover, the study examines the ethical considerations of AI integration, such as transparency, bias mitigation, and privacy protection, aiming to maximize its benefits while addressing potential limitations in clinical practice.[1-10]

2. Epilepsy: The impact and importance of early diagnosis and treatment

The International League Against Epilepsy (ILAE) defines epilepsy as a disease of the brain characterized by any of the following conditions: at least two unprovoked (or reflex) seizures occurring more than 24 h apart, one unprovoked (or reflex) seizure with a probability of further seizures similar to the general recurrence risk (at least 60%) after two unprovoked seizures over the next 10 years, or a diagnosis of an epilepsy syndrome.[11,12] Epilepsy affects approximately 65 million individuals worldwide, with around 80% of cases occurring in developing regions (World Health Organization [WHO], 2020).[13] Epilepsy can be classified into various types based on the nature and origin of the seizures,[14] primarily categorized into generalized and focal seizures.[13] Understanding these classification are crucial for effective diagnosis and treatment, highlighting the need for continuous research and refinement of diagnostic criteria.[12] Early diagnosis and treatment are crucial for improving the quality of life for those affected by epilepsy and for preventing complications associated with this chronic neurological disorder.[13,14] Advanced technology, particularly AI, is transforming the diagnosis and management of epilepsy by providing new tools to detect and predict seizures with increasing accuracy.[15] The prevalence of epilepsy varies globally, impacting 0.6 – 1.0% of the population, with higher rates observed in developing regions (0.7 – 1.2%) compared to developed regions (0.5 – 0.8%).[16] This disparity highlights the urgent need for enhanced diagnostic and treatment resources in under-resourced areas, where epilepsy care is often limited or unavailable (WHO, 2020).[1] Diagnosis typically involves a detailed history, semiology examination, and electrophysiological methods to identify the epileptic focus and classify the type of seizures.[10,11] Treatment primarily includes long-term use of antiseizure medications (ASMs) to reduce seizure frequency or achieve remission, with careful monitoring for adverse reactions.[8] The primary goal in conventional epilepsy management is to control seizures, minimize side effects, and improve quality of life.[8,9] This includes accurate diagnosis using EEG and magnetic resonance imaging (MRI) to classify seizure types and guide treatment choices.[8,9] First-line treatment typically involves ASDs, like carbamazepine or valproate, often using monotherapy to minimize interactions.[10,11] For drug-resistant cases, surgical interventions or alternative treatments, such as vagus nerve stimulation and ketogenic diets, may be applied.[10,11] Lifestyle adjustments and psychosocial support, alongside regular monitoring, are crucial for effective ongoing management and treatment sucess.[8-11]

3. Challenges in epilepsy education and awareness

Epilepsy education faces numerous challenges, including inadequate knowledge and awareness, as well as significant disparities in care and educational needs.[17] One of the primary issues is the poor knowledge and awareness about epilepsy among patients, which hampers effective self-management and diminishes the quality of life.[14] This lack of awareness extends to the public and healthcare professionals, contributing to the under-recognition

of seizures and delays in diagnosis and treatment.[16] In educational settings, there is a pressing need for well-designed teaching units on epilepsy that encompass basic knowledge, neuronal processes, and first aid measures.[18] However, challenges such as accommodating students with epilepsy in the classroom, ensuring adequate preparation time, and preventing anxiety among students must be addressed.[15] In addition, children and adolescents with epilepsy often face emotional, cognitive, and social challenges that impact their school experience, leading to learning difficulties, such as dyslexia, spelling disorders, and dyscalculia.[17] For healthcare professionals, particularly pediatric neurologists, significant challenges include integrating guidelines into practice, identifying epilepsy events, incorporating genetic testing, and transitioning from pediatric to adult care – all of which require targeted educational interventions.[1] Moreover, people with epilepsy in low- and middle-income countries face substantial barriers to quality care, including language, economic, and technological barriers, that further complicate educational efforts.[16] Addressing these multifaceted challenges requires a comprehensive approach that includes public education, specialized training for healthcare providers, and tailored educational programs in schools to improve the overall management and quality of life for individuals with epilepsy.

Epilepsy education for neurologists faces several challenges, as highlighted by various studies. A significant issue is the limited evidence base for treating seizures in adults with neurodevelopmental disorders, complicating the management of epilepsy in this population.[1] This challenge is exacerbated by higher rates of physical and psychiatric comorbidities, polypharmacy, and neuropsychiatric side effects of medications, necessitating a nuanced treatment approach that lacks robust Level 1 evidence.[18] In addition, while achieving seizure freedom is a primary goal, many neurologists lack confidence in optimizing the dosing of ASMs in combination therapies, as evidenced by a continuing medical education (CME) certified activity that showed only a minimal educational effect in this area.[19] Another barrier is the underutilization of epilepsy surgery, despite its recognition as a valid early intervention.[19] Many physicians refer patients for surgery only after the failure of multiple ASMs, often due to an overestimation of surgical risks and inadequate healthcare resources.[20] Furthermore, there is a gap in pre-service and ongoing education about epilepsy, including first-aid measures and neuronal processes. Enhancing this education could significantly improve the quality of life for individuals with epilepsy if better integrated into medical education.[15] These multifaceted challenges underscore the need for comprehensive, evidence-based educational programs and resources to better equip neurologists in effectively managing epilepsy.[19]

Epilepsy awareness faces numerous challenges globally, significantly impacting the quality of life for individuals with epilepsy.[20] Misconceptions and stigma are rampant, with epilepsy often misunderstood as a psychiatric or contagious disease in various regions, further complicating access to appropriate care and treatment. Stigma manifests in several forms – internalized, interpersonal, and institutional – creating significant barriers for patients and preventing them from seeking help and fully participating in society.[21] In addition, barriers to care are intensified by economic, language, and technological challenges, particularly in low- and middle-income countries where 80% of epilepsy patients reside.[16] These barriers lead to delays in diagnosis and treatment, resulting in many individuals with epilepsy not receiving optimal seizure control or access to necessary surgical options.[16] Furthermore, awareness and research on epilepsy-related deaths, such as sudden unexpected death in epilepsy (SUDEP), are still evolving, highlighting the need for more comprehensive practices among health professionals to enhance prevention and epidemiological surveillance.[22] Overall, enhancing epilepsy awareness requires a multifaceted approach involving education, policy reform, and community support to dismantle the barriers faced by these patients. Figure 1 illustrates the distribution of publications across various regions globally, highlighting efforts in AI-driven epilepsy education

4. Transforming education with AI: Personalized learning, enhanced instruction, and professional development in healthcare

AI is transforming the educational landscape by enhancing learning, teaching, and administration methods.[23] AI-powered adaptive learning mechanisms personalize education by constructing tailored educational pathways based on student performance data, which enhances overall engagement and academic achievements.[23] AI technologies, such as ChatGPT, have opened new possibilities for educational practices, allowing teachers to create study materials, presentation media, and evaluation tracks with greater ease and efficacy while facilitating personalized learning tailored to each student's unique needs.[24]

AI applications in education, such as chatbots, learning analytics, and intelligent tutoring systems, enable data-driven decision-making and streamline administration, although they also raise ethical dilemmas.[25] In general, AI in education presents new opportunities to improve learning outcomes for students, preparing them to succeed

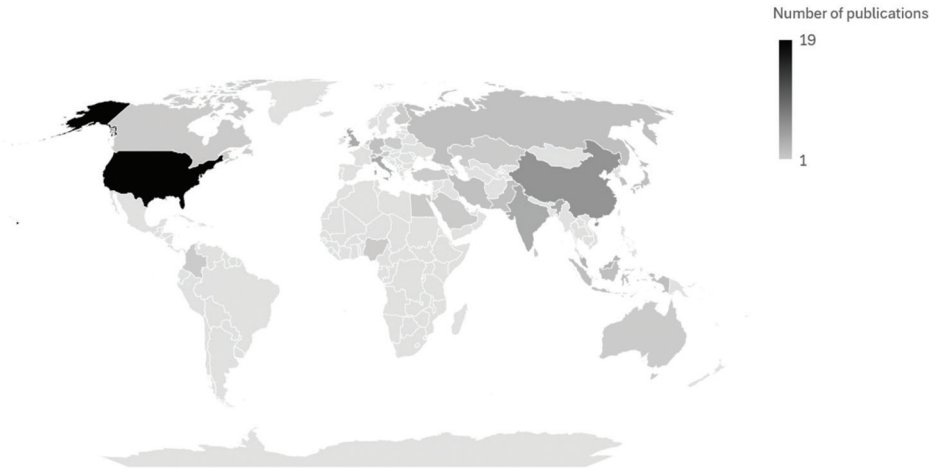


Figure 1. Distribution of artificial intelligence-driven epilepsy education publications across various regions globally

in the digital age.[23,25,26] AI-enabled personalized learning systems offer a potentially transformative educational strategy that utilizes advanced technology to benefit individual students.[27] Online education with AI assistants provides customized recommendations for monitoring performances, suggesting relevant topics, and structuring individual learning programs. This approach addresses the drawbacks of traditional systems while fostering the development of academic and soft skills.[28] AI-based recommendation algorithms have proven effective in personalizing teaching content, improving student outcomes, and increasing satisfaction by recommending appropriate content based on multi-dimensional information, such as students' interests and learning histories.[29] AI is increasingly integrated into CME and training, offering significant potential to enhance learning outcomes and professional development for healthcare providers. AI's ability to answer CME quiz questions with high accuracy was demonstrated by a study where AI completed 90% of quizzes with an 86% accuracy rate, underscoring its capability in this domain.[30] Integrating AI into postgraduate training can enhance personalized learning, provide real-time feedback, and assist in decision-making processes for healthcare professionals. Beyond CME, AI's role in medical education includes delivering personalized learning experiences and improving practical skills, as evidenced by improved outcomes in training labs and other educational settings.[31,32]

5. Empowering epilepsy management through mobile health applications and gamification

There is relative success in knowledge enhancement, medication compliance, and overall seizure control through mobile applications and gamification for patient education in epilepsy.[33] The development of mobile health applications is increasing, particularly to support chronic disease management, with a strong focus on epilepsy patients. These applications cover various aspects, including stress management, drug side effect monitoring, patient education, and adherence promotion.[33] They utilize simple games and role-playing activities centered around epilepsy, delivering essential information through interactivity and storytelling, which fosters better user engagement and encourages a respectful, tolerant community toward epilepsy.[34]

These digital tools empower patients to take control of their healthcare by allowing them to share health records and emotional states with neurologists while receiving close support from dedicated care managers.[35] For instance, the mobile application – ThinkNinja for Epilepsy – has provides cognitive behavioral therapy interventions to enhance the quality of life and mental health of individuals with epilepsy and anxiety, thereby improving overall well-being for those with comorbid anxiety or depression.[35] Other applications, such as Epilepsy Journal, Seizure Tracker, Helpilepsy, and Seizure First Aid, help monitor seizures, record medication intake, offer emergency treatment advice, and adjust dosage regimens. This functionality reduces risks associated with ASMs and promotes better patient compliance.[36]

6. Revolutionizing epilepsy education: AI-powered simulation-based learning (SBL) and training modules for healthcare professionals

Integrating AI into SBL will transform the training of healthcare professionals in epilepsy education.[37,38] Management of epilepsy is highly individualized, making

it essential for AI to fine-tune and customize learning pathways; without this personalization, achieving mastery and timely interventions may prove difficult.[39] AI tools, like ChatGPT, can aid in enabling simulation-based training by providing realistic and interactive scenarios that mimic practical epilepsy cases, thereby improving diagnostic accuracy and decision-making.[40] The incorporation of AI in SBL can also address the challenge of low-frequency, high-risk events, such as pediatric seizures, by allowing healthcare workers to practice and refine their skills repeatedly in a controlled environment.[40] This approach not only enhances technical and cognitive skills but also boosts self-efficacy and confidence among providers, leading to improved performance in simulated settings.[40]

It has been reported that AI-based automated seizure detection systems exhibit remarkable capabilities in developing models for accurate diagnosis and interpretation of EEG patterns, significantly reducing the risk of human error.[41] These systems can analyze vast amounts of EEG data within very short periods, consistently identifying subtle patterns that may elude human detection, thereby enhancing the overall efficacy of the diagnostic process.[41] With AI support, the likelihood of misdiagnosis is significantly reduced, as these systems are trained to identify specific patterns associated with epileptic seizures, resulting in more consistent outcomes.[41] The integration of AI within the SBL framework aligns with the broader trend of using intelligent tutoring systems and role-plays involving active agents that engage learners' sense of responsibility.[42] Continuous improvement of AI-driven SBL methods, incorporating feedback from both learners and educators, could greatly benefit healthcare professionals' training in epilepsy management, ultimately enhancing patient outcomes and healthcare delivery.[38,43] These advancements are expected to significantly improve epilepsy education for medical professionals by providing personalized, effective, and accessible learning experiences through these training modules.[41]

The ILAE Academy served as a structured online learning venue featuring self-paced, interactive modules based on competency-led curricula in epileptology, catering to both entry and proficiency levels.[44,45] On this case-based platform, AI can enhance the educational experience through intelligent tutoring systems and individualized feedback, alongside relevant clinical practice and an online EEG and MRI reader complemented with live-tutored courses for CME credits.[46] AI's capabilities in pattern recognition and data-driven decision-making can significantly improve the precision of disease diagnosis and treatment – which is vital in epilepsy management.[44] Furthermore, AI is being used for seizure forecasting, predicting possible seizure occurrences based on historical data and current EEG readings, thereby allowing patients and caregivers time to plan accordingly.[45] Figure 2 shows the flowchart diagram illustrating the steps in EEG-based epilepsy management using machine learning.

7. Comparative analysis of machine learning models for epilepsy detection using EEG data

AI is increasingly transforming epilepsy management through applications that encompass diagnostic support, seizure prediction, treatment personalization, and patient education.[46] Each AI model offers distinct advantages tailored to different aspects of epilepsy care.[47] For instance, convolutional neural networks (CNNs) have become a critical tool in processing EEG data, enhancing the precision of seizure classification.[46,47] Similarly, recurrent neural networks (RNNs) are well-suited for predicting seizures due to their capability to interpret time-sequential data, which is critical in assessing patterns in EEG recordings.[46,47]

Below is a comparative analysis of various AI models frequently applied in epilepsy management, highlighting

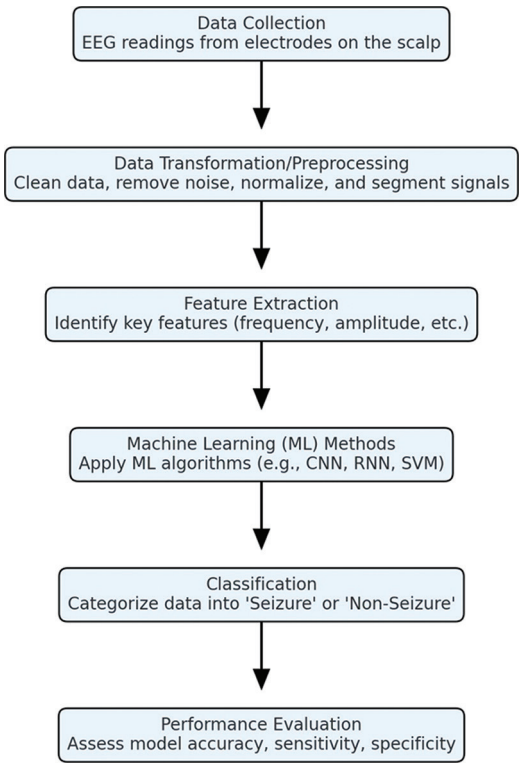


Figure 2. Electroencephalography-based epilepsy detection workflow using machine learning
Abbreviations: CNN: Convolutional neural network; EEG: Electroencephalography; RNN: Recurrent neural networks; SVM: Support vector machines.

their primary applications, strengths, and limitations. This table aims to give a concise overview of each model's role and applicability in addressing the unique challenges presented in epilepsy care. Table 1 shows the characteristic features of different AI applications in epilepsy management.

Several studies have explored machine learning models for detecting epileptic seizures based on EEG data, achieving varying degrees of accuracy, sensitivity, and specificity.[48-56] Hannun *et al.*[45] developed a CNN for seizure detection, achieving an accuracy of 95.6%, sensitivity of 93.2%, and specificity of 96.5%.[47] However, when compared with the lightweight triscale yielding-CNN model by Yang *et al.*,[48] which attained an accuracy of 99.9% on the SWEC-ETHZ dataset, Rajpurkar's CNN shows slightly reduced accuracy while still being a practical approach for seizure detection.[45] Similarly, Mirowski *et al.*[49] applied support vector machines (SVM) for heart rate-based seizure detection and obtained an accuracy of 91.4%, with a sensitivity of 89.2%, and a specificity of 92.5%.[49] This was lower than the results reported by Pedersen *et al.*,[50] who also used SVM with relative energy features from discrete wavelet transform, achieving a higher accuracy of 98%.[50]

In a different approach, Balta[51] used a random forest classifier for early seizure detection on EEG data, achieving an accuracy of 90.8%, sensitivity of 88.5%, and specificity of 91.9%.[51] In contrast, Huang[52] achieved over 96% accuracy using a random forest with intracranial EEG data, showing that model performance can vary substantially across different datasets.[52] Pascual *et al.*,[53] used a long short-term memory (LSTM) model to capture temporal dependencies within EEG signals, reporting an accuracy of 94.2%, sensitivity of 92.1%, and specificity of 95.2%.[53] In comparison, Zhao *et al.*[56] implemented a residual bidirectional LSTM (ResBiLSTM) model, achieving up to 100% accuracy in binary classification, indicating a marked improvement over Zhang's approach, particularly in managing temporal dependencies.[56] Lastly, Mbiazi *et al.*[57] deployed a RNN model for seizure prediction, reporting an accuracy of 92.1%, sensitivity of 90.5%, and specificity of 93.3%, which demonstrates solid predictive capability, although it falls short of the advanced accuracy levels achieved by models like ResBiLSTM.[56]

These studies collectively illustrate the strengths and limitations of various machine learning models in epilepsy detection.[49-57] Although CNN and LSTM models consistently demonstrate high sensitivity and specificity, their performance can vary based on dataset characteristics and model refinements.[49-51] Models, like ResBiLSTM, show that integrating bidirectional temporal processing can enhance accuracy, especially in binary classification.[56] The effectiveness of each model appears linked to specific factors, such as EEG data type, temporal analysis, and feature extraction techniques, underscoring the importance of selecting models based on the dataset and clinical application requirements.[56,58] This comparative analysis highlights the promise of refined neural network architectures, particularly for achieving near-perfect accuracy in seizure detection. Table 2 shows an overview of AI models currently utilized for epilepsy diagnosis and prediction.

8. Leading institutions in AI epilepsy research

Institutions worldwide are making significant strides in applying AI technologies to improve epilepsy management.[58-60] The National Institute of Neurological Disorders and Stroke is at the forefront, conducting pioneering research in CNNs to enhance seizure prediction capabilities.[58-60] The Epilepsy Foundation is actively funding projects focused on AI-driven seizure detection to introduce innovative solutions into clinical practice.[58,59] At the University of California, Los Angeles, researchers are developing RNN-based diagnostic tools that promise earlier and more accurate epilepsy detection.[58,59] The University of Oxford is advancing AI-powered EEG analysis, which is essential for precise seizure monitoring.[60]

Table 1. Comparative analysis of AI applications in epilepsy management by type of model and purpose

AI model	Primary application	Advantages	Limitations
CNN[45]	EEG signal classification	High accuracy in pattern recognition	Computationally intensive
RNN[45,46]	Seizure prediction and temporal analysis	Suitable for time-series data	Requires large datasets
SVM[47]	Feature-based EEG classification	Effective for small datasets	Limited flexibility with complex data
Decision trees[47]	Patient outcome prediction	Easy interpretability	Prone to overfitting in high-dimensional data
Transfer learning[48]	Adaptation to specific patient groups	Reduces the need for extensive training data	Requires pre-trained, similar domain models
Reinforcement learning[47,48]	Personalized treatment and adherence	Dynamic adaptation to patient needs	Complex to train and validate in healthcare

Abbreviations: CNN: Convolutional neural network; EEG: Electroencephalography; RNN: Recurrent neural networks; SVM: Support vector machines.

Meanwhile, Harvard Medical School is working on LSTM-based models for real-time seizure prediction, which are vital tools for mitigating risks associated with SUDEP and enhancing patient safety.[61] Collectively, these institutions are shaping the future of epilepsy care by creating accessible, accurate diagnostic tools that significantly improve patient outcomes globally.[58-61] Table 3 highlights the contributions of these institutions in advancing AI's role in epilepsy management.

9. Case studies and practical implementations

Various research efforts have underscored the utility of AI in epilepsy outreach and the central goals within this field.[57] AI models for detecting and forecasting epileptiform EEG patterns and seizures have yielded significant outcomes in clinical applications.[58] For instance, the AI-based model mjn-SERAS exhibits notable sensitivity and specificity in early seizure detection using customized mathematical models for individualized patient care through EEG analysis.[59] Research highlights specific AI applications in epilepsy, focusing on seizure detection, prediction, and localization.[59] Jeon *et al.*[60] demonstrated a deep-learning model for identifying epileptiform discharges in self-limited epilepsy, achieving high specificity and sensitivity.[60] This model reduced false positives, thus aiding accurate early diagnosis.[60] Similarly, Altaheri *et al.*[61] applied a deep learning-based EEG analysis method that enhanced detection rates and simplified the identification of complex seizure patterns, improving real-time clinical interventions.[61] Another study that incorporated predictive models using EEG and electrocardiogram (ECG) data achieved high performance in seizure prediction, facilitating timely interventions and comprehensive patient monitoring.[63] These examples illustrate the advancement of engineering science in utilizing AI to enhance epilepsy diagnosis, streamline clinical workflows, and support informed decision-making in patient care.[60-63]

10. Barriers to AI adoption in healthcare and education

Despite the need to integrate AI into teaching, learning, and healthcare, several challenges must be addressed to facilitate better integration.[54,55] Concerns include a lack of technical proficiency in medical schools, often stemming from inaccurate descriptions and volunteered information given by generative intelligence models.[61] In addition, issues related to data privacy, moral and legal aspects, compatibility issues, and complexities in human-AI communication hinder the integration of AI in

Table 2. Key findings of machine learning models for detecting epileptic seizures based on electroencephalogram

Authors	Year	Type of study	Results (Statistical values)
Hannun *et al.*[47]	2019	Deep neural network for arrhythmia detection	ROC AUC: 0.97, F1 Score: 0.837
Zhou *et al.*[48]	2024	Heartbeat classification using CNNs and transformer	Accuracy: 99.4%
Siddiqui *et al.*[49]	2020	Review of machine learning classifiers for seizure detection	Overview of classifiers and features
Yang *et al.*[50]	2022	An AI system for clinical seizure recognition	High sensitivity and specificity
Mirowski *et al.*[51]	2019	Comparison of SVM and CNN for seizure prediction	High accuracy, CNN slightly better

Abbreviations: AUC: Area under the curve; CNN: Convolutional neural network; LSTM: Long short-term memory; RNN: Recurrent neural network; ROC: Receiver operating characteristic; SVM: Support vector machine.

Table 3. Contributions of different institutions in advancing artificial intelligence in epilepsy management

Institution	Location	Key focus areas in epilepsy AI	Selected contributions
Mayo Clinic	USA	EEG signal analysis, seizure prediction, patient monitoring	Mayo Clinic AI Lab on Epilepsy
Boston Children's Hospital	USA	Pediatric epilepsy, EEG monitoring, and AI-driven educational resources	AI-EEG study for early seizure diagnosis
University College London	UK	EEG and MRI imaging analysis, epilepsy surgery decision support	UCL AI for epilepsy diagnostics
Seoul National University	South Korea	Machine learning for seizure classification, patient adherence strategies	Epilepsy AI Lab, Seoul National University
Indian Institute of Science	India	Deep learning for EEG analysis and epilepsy care in low-resource settings	Epilepsy AI in developing regions
WHO Collaborating Centre on Epilepsy	International	Ethical and social aspects of AI in epilepsy global access to AI diagnostics	WHO Report on AI in Epilepsy[62]

Abbreviations: AI: Artificial intelligence; EEG: Electroencephalography; MRI: Magnetic resonance imaging; UCL: University College London; UK: United Kingdom, USA: United States of America; WHO: World Health Organization.

healthcare interventions.[63] Healthcare professionals must develop digital skills, understand legal and ethical issues, and enhance their eHealth literacy to promote the safe and efficient integration of AI.[64] Furthermore, language barriers in online medical education can be mitigated through AI-generated multilingual educational materials, ensuring global harmonization of healthcare practices and adherence to digital health standards.[64]

11. Potential negative aspects of AI in epilepsy management

AI systems can inadvertently perpetuate biases in training data, leading to diagnostic inaccuracies for certain demographics.[65] Research by Theodore *et al.*[65] highlights that biases in seizure data may result in inequitable epilepsy care for underrepresented groups.[65] In addition, using vast medical data in AI raises privacy concerns.[65] Timan and Mann[64] emphasize that strict data protection protocols are essential to prevent misuse and maintain patient trust in AI-driven treatments.[64] Many AI models operate as "black boxes," making it difficult to trace decision-making pathways.[64] Wang *et al.*[66] stress the need for transparent AI systems with defined accountability to ensure safe management in epilepsy care.[67] Excessive reliance on AI could erode clinicians' judgment and diagnostic skills.[67] Shoeibi *et al.*[67] suggest that balancing AI assistance with clinical experience is crucial to retaining essential skills for managing complex epilepsy cases.[67] Routine use of AI may diminish critical thinking, affecting clinicians' ability to manage epilepsy effectively without AI support.[67] Continuous training is recommended to mitigate skill erosion.[68] Assigning responsibility for AI-driven errors is complex.[68] Robust frameworks are necessary to address accountability, especially in cases where AI misdiagnoses epilepsy-related events.[62] The use of AI may also depersonalize patient interactions, potentially impacting patient satisfaction.[62] Evidence-based data supports the necessity of human oversight in AI-augmented care to preserve empathy and trust,[62] as epilepsy's intricate management often requires personalized approaches that AI alone may not fully address.[62] Recent guidelines suggest AI should support, not replace, individualized care.[62] Ongoing audits and ethical standards are essential to prevent unintended harm.[62,69] Timan and Mann[64] advocate for regular evaluations to ensure AI aligns with ethical healthcare practices.[64,66] Comprehensive regulations are vital to ensure the safety, reliability, and fairness of AI applications in healthcare.[65] Recent studies underscore the need for robust national and international guidelines to effectively govern the use of AI technologies in clinical settings.[64-69]

12. Ethical and regulatory challenges in AI-driven epilepsy management and education: Balancing innovation with patient-centered care

The integration of AI in epilepsy management and education raises several ethical and regulatory concerns that are essential to address for equitable and effective patient care.[65] A major issue is bias and fairness; AI models can inadvertently propagate biases embedded within the training data, potentially causing disparities in treatment outcomes across diverse demographics.[64] For instance, an AI system trained on data representing a particular demographic may underperform for underrepresented groups, thereby amplifying existing healthcare inequalities.[66] This emphasizes the need for diverse data representation to prevent unequal treatment and foster fairness in AI-driven healthcare applications.[66] Privacy and data security are also critical considerations, especially given the sensitive nature of patient data managed by AI in healthcare.[66] In epilepsy diagnosis, vast amounts of labeled datasets containing personal information are required, posing risks to personal data privacy.[66] Breaches in data privacy could lead to identity theft, discrimination, and diminished trust in healthcare systems.[66] Furthermore, data transmitted over networks, such as EEG recordings, are vulnerable to cyber-attacks.[66] However, innovative strategies, like encrypted EEG data classification using advanced algorithms and CNNs, show promise in enhancing data security and privacy.[67] This highlights the importance of robust measures to safeguard patient privacy and ensure data security in AI-based epilepsy care.[67] Informed consent is fundamental for patient autonomy; individuals must understand how their data will be used and the potential benefits and risks of AI interventions.[58] However, obtaining informed consent can be challenging due to the complexity of AI technologies, which may hinder patients' ability to fully comprehend the implications of AI-driven care.[58] Transparent communication and clear consent processes are necessary to uphold patient rights and build trust.[58] Transparency and accountability in AI systems are also crucial.[53] Many AI models function as "black boxes," making it difficult to interpret how specific conclusions are reached.[53] This lack of transparency can obscure accountability, especially when adverse outcomes arise.[59] Regulatory frameworks that mandate transparency and define responsibility among healthcare providers, AI developers, and system manufacturers are essential to address these challenges effectively.[59] Over-reliance on AI in clinical settings can lead to "de-responsibilization," where healthcare professionals may experience a decline in critical thinking and clinical judgment.[59] If professionals become overly dependent on AI tools, they may lose vigilance in

assessing the multifaceted aspects of epilepsy, potentially missing nuances critical to patient care.[66] Striking a balance between AI assistance and human expertise is necessary to prevent the erosion of clinical judgment.[66] In addition, skill degradation is a risk; reliance on AI for routine tasks can weaken healthcare providers' ability to perform essential clinical functions independently.[67] Continuous training is needed to ensure professionals retain their expertise and remain prepared for situations where AI tools may be unavailable or malfunctioning.[68]

Ethical issues in AI deployment encompass fairness, privacy, safety, transparency, and explainability.[64-67] In the pharmaceutical industry, the use of AI in drug discovery has raised risks and ethical concerns, particularly regarding patient care outcomes and data privacy.[67] Addressing these ethical challenges requires AI systems to be transparent, accountable, fair, and genuine, especially in educational settings where AI's role is growing.[68] The inclusion of AI in medical training programs should focus on its complementary role to traditional learning methods, reinforcing critical thinking and clinical judgment skills among neurophysicians and other healthcare professionals.[68] The impact of AI on patient experiences and the patient-provider relationship is another crucial consideration.[68] As AI assumes a larger role in decision-making, patients may perceive that decisions are increasingly driven by algorithms rather than human judgment, potentially weakening the personal connection and empathy central to healthcare.[68] A human-centered approach that integrates AI insights with personalized care is essential for maintaining trust and compassion in patient interactions.[68] Furthermore, epilepsy management requires personalized care plans that combine AI-generated insights with clinical expertise to meet the complex needs of each patient.[68]

To ensure the ethical use of AI in epilepsy care, continuous monitoring and adherence to ethical standards are imperative.[64-68] Establishing regulatory frameworks, conducting regular audits, and implementing ethical safeguards can help prevent unintended harm while ensuring that AI systems align with healthcare's ethical principles.[64-68] By recognizing and proactively addressing these ethical and societal considerations, stakeholders can maximize AI's potential to improve epilepsy care while safeguarding patient welfare.[64-68] This requires ongoing dialogue among healthcare providers, patients, AI developers, and policymakers to navigate challenges and leverage the benefits of AI effectively.[64-68]

13. Future research directions and emerging trends

Future research directions and trends in AI for epilepsy education include using natural language processing (NLP) to analyze clinical and textual data within epilepsy care.[66] NLP tools are advancing to better interpret unstructured data from patient records, notes, and academic literature, facilitating more streamlined and accessible epilepsy information. Deep learning models, including few-shot learning, metric learning, and capsule neural networks, have shown promise in tackling data scarcity and enhancing diagnostic accuracy in epilepsy.[67] These enable robust pattern recognition even with limited datasets, which is particularly beneficial for rare and complex seizure disorders.

EEG signal processing remains a critical challenge in these applications, particularly in noise removal and feature extraction. Ongoing efforts aim to design AI prediction tools with high sensitivity and specificity to improve real-time seizure prediction, which could enable preemptive interventions and enhance patient quality of life.[68] For example, the development of mobile applications for epileptic seizure detection based on EEG signals demonstrates the importance of user-friendly tools that leverage advanced algorithms for practical uses.[62]

One area of ongoing exploration is the integration of multimodal data, such as EEG, ECG, and imaging data, to further refine seizure prediction algorithms. The potential for wearable technology and mobile health applications is being leveraged to support continuous monitoring and allow real-time data collection.[68] Such devices can potentially improve patient autonomy by providing early warnings and individualized feedback based on AI-driven analysis. Simultaneously, techniques for baseline removal in EEG signal processing are paving the way for more accurate and subject-independent emotion classification.[69]

Collaborative frameworks are also evolving to foster data sharing and enhance epilepsy research across institutions.[70] For example, federated learning enables institutions to collaborate on AI models without sharing sensitive patient data directly, thereby protecting privacy while advancing collective knowledge.[70] These frameworks are essential for scaling AI research and ensuring that AI models are trained on diverse datasets that reflect a broader patient population.[70] Ultimately, as AI in epilepsy diagnosis and management progresses, collaboration with healthcare providers and regulatory bodies is vital to ensure that novel models or devices meet clinical standards, maintain patient safety, and support personalized patient care.[70] With these advancements, AI can continue to evolve as a transformative tool in epilepsy treatment and diagnosis, helping to bridge gaps in healthcare access, refine precision medicine approaches, and improve outcomes for epilepsy patients worldwide.[71]

14. Conclusion

The role of AI in epilepsy management is undeniably transformative, offering unprecedented opportunities for improving patient outcomes. AI technologies have shown remarkable efficacy in early diagnosis, seizure prediction, and personalized treatment, which are critical for enhancing the quality of life for individuals with epilepsy. Integrating AI in wearable devices and mobile health platforms has facilitated continuous monitoring and patient engagement, contributing to more effective and timely interventions. However, the implementation of AI in clinical practice presents challenges. Issues related to data privacy, ethical considerations, and the need for rigorous clinical validation must be addressed to realize the potential of AI in epilepsy care. Future research should focus on overcoming these barriers and exploring innovative AI applications to further advance epilepsy management. Collaborative efforts among researchers, clinicians, and technology developers are essential to harness the full potential of AI, ultimately leading to better health outcomes for individuals with epilepsy.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare no conflicts of interest.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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