International Journal of Pharmacy and Pharmaceutical Research (IJPPR)
Volume 32, Issue 3, March 2026 ijppr.humanjournals.com ISSN: 2349-7203

Personalized Medicine in Epilepsy Management: Current Trends and Future Perspectives

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Received: 18 January 2026 Revised: 30 January 2026 Accepted: 19 February 2026

ABSTRACT

Personalized medicine represents an evolving paradigm in epilepsy management, aiming to tailor therapeutic strategies based on individual genetic, molecular, and clinical characteristics. Epilepsy is a complex and heterogeneous neurological disorder affecting millions worldwide, with significant variability in disease manifestation and response to treatment. Conventional antiseizure drug therapy often follows a trial-and-error approach, which may lead to suboptimal seizure control and adverse drug reactions. Advances in pharmacogenomics have enabled the identification of genetic variations influencing drug metabolism, efficacy, and safety, thereby supporting precision-based treatment selection. The use of biomarkers has further enhanced early diagnosis, disease stratification, and prediction of therapeutic outcomes. Emerging technologies such as three-dimensional (3D) printing have opened new avenues for personalized drug delivery systems, allowing customized dosage forms to improve adherence and therapeutic precision. Additionally, artificial intelligence (AI) and digital health tools have significantly contributed to automated seizure detection, predictive modeling, and real-time monitoring, enhancing both diagnosis and long-term management. Despite challenges related to ethical considerations, data standardization, and regulatory frameworks, the integration of genomics, AI, and advanced drug delivery technologies holds great promise. Personalized medicine is expected to redefine epilepsy care by shifting from generalized treatment approaches to individualized interventions, ultimately improving patient outcomes and quality of life.

Keywords: Personalized medicine; Epilepsy; Pharmacogenomics; Biomarkers; Artificial intelligence; 3D printing; Precision medicine; Antiseizure medications.

INTRODUCTION

1.1 Personalized Medicine:

The phrase "personalized medicine" has gained popularity recently, in part because to advancements like the Human Genome Project and in part because medications are rarely 100% safe and effective. Many people think that these advancements will increase our ability to prevent and treat a variety of diseases by enabling the identification of subtypes of various diseases based on genetics in addition to other methods like histology.

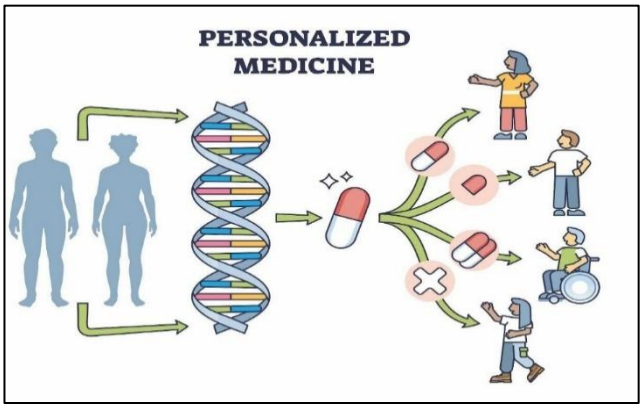

Figure 1: Personalized Medicine

Genetic information, for instance, may be used to assess whether individuals with particular disease subtypes are more likely than others to respond to a given medication (both new and old). On the surface, it appears like everyone agrees on what personalized medicine means. However, a closer look at the current definitions of customized medicine shows significant differences amongst them. Personalized medicine, for instance, has been described as

1. "A medical model that suggests using genetic or other data to customize healthcare, with decisions and practices being tailored to the individual patient."

2. "The customization of medical care to each patient's unique characteristics". It does not literally refer to the development of patient-specific medications or medical equipment. Instead, it entails the capacity to group people into subpopulations that are disproportionately or uniquely prone to a given illness or receptive to a given treatment.

3. "A type of medicine that prevents, diagnoses, and treats disease by using information about an individual's genes, proteins, and environment."(1)

1.2 A Legal History of Personalized Medicine

The idea of genetic privacy gained attention as the importance of genetics in medicine increased. Knowing someone is prone to an illness, even before they exhibit symptoms, can either be a valuable tool for enhancing their health and quality of life or it can be used to discriminate against them in the workplace, restrict their access to insurance, and other services. An analysis of the legal environment around genetic privacy reveals that it is evolving alongside technological advancements and the acceptance of customized treatment.

In Katz v. United States (389 US 347 [1967]), the Supreme Court declared that there is no "general constitutional right to privacy." Instead, the protection of an individual's right to privacy is primarily left to state law, much like the protection of his property and life. Nonetheless, the courts have acknowledged, to some extent, the expectations of privacy surrounding medical information, and privacy and secrecy are fundamental principles of medical ethics. (2)

1.3 Epilepsy:

Epilepsy is the second most prevalent neurological condition after stroke, affecting up to 1% of the population. Approximately 50 million individuals globally suffer from epilepsy. and 90% of them are from underdeveloped nations. In the last few years, there has been a significant improvement in how epilepsy is perceived. It is a prevalent long-term neurological condition marked by frequent unprovoked epileptic seizures, where the balance between brain excitability and inhibition favors unchecked excitability. (7)

Figure 2: Epilepsy

Epilepsy diagnosis is still difficult and resource-intensive despite advancements in medical technology. Differentiating between epileptic and non-epileptic episodes, such as syncope or psychogenic non-epileptic seizures (PNES), is necessary for an accurate diagnosis. The sensitivity and specificity of conventional diagnostic EEG and MRI are frequently limited, especially in the interictal period when seizures are not present. (9)

In the pathophysiology of epilepsy, the terms hypersynchrony and hyperexcitability are distinct but have similar meanings. Hyperexcitability is the term used to describe neurons' aberrant response to stimuli. This disorder is caused by neurons that fire too many nerve cells in the brain as a result of reacting too intensely to messages from other cells. Hypersynchrony is the term used to describe the regular occurrence of many neurons initiating electrical activity. Several nearby neurons are involved in abnormal electrical bursts. In this instance, aberrant stimulation first affects a small number of neurons. An epileptic seizure is caused by a shift in the synaptic gap's usual inhibitory ion exchange and membrane conductance, which increases neuronal excitability and synchronization. Usually, changes to synapse function and intrinsic neuronal components cause hyperexcitability. Mutations in ion channel genes are thought to cause a number of different forms of human epilepsy, according to advancements in molecular genetics. In order to contribute to a deeper comprehension of the etiological intricacies inherent in epileptogenesis, this article will thoroughly examine the complex molecular foundations that give rise to epileptic seizures and the overall epileptic condition.(5)

1.4 Causes of epilepsy

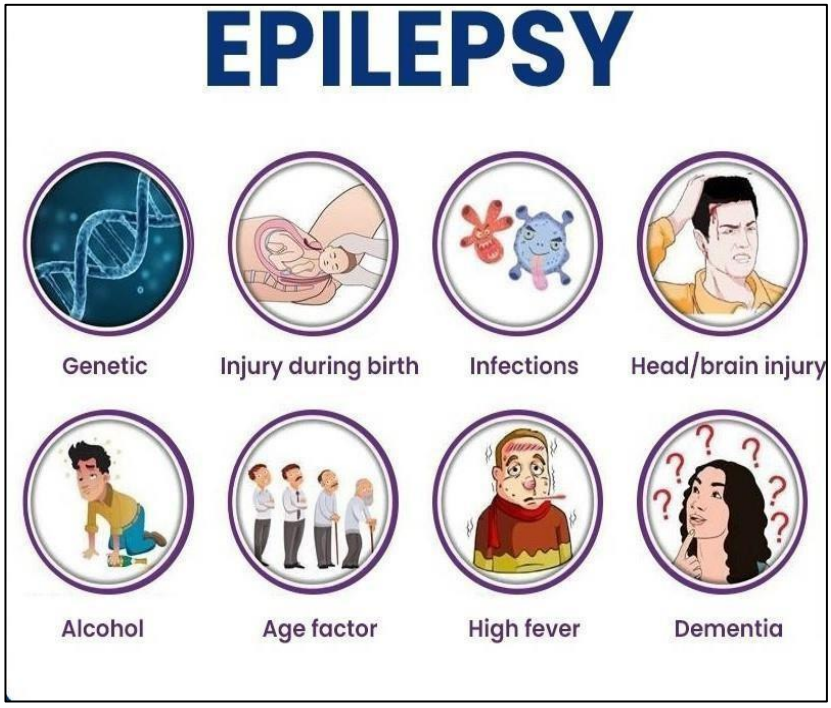

Figure 3: Causes of Epilepsy

The exact cause of epilepsy is uncertain. The term "epilepsy" does not describe the reason or severity of seizures in a person; while some cases of epilepsy are brought on by genetic factors, other causes include brain injuries from head trauma, strokes, infections, high fevers, or tumors. It has been shown that while genetics can influence persons of any age, heredity plays a significant role in many causes of epilepsy in very young children. Even while severe head trauma is a known cause of epileptic seizures, not everyone who experiences it will go on to acquire epilepsy. (7)

Even though they do not directly impact the brain, severe systemic infections can increase the risk of seizures by causing metabolic dysfunction, pyrexia, cytokine release, and autoimmunity. Cerebral infections will be our main topic here. Among the most frequent causes of seizures and epilepsy globally, cerebral infections brought on by bacteria, viruses, fungi, and parasites are especially widespread in underdeveloped nations. (3)

1.4.1 Genetic Causes of Epilepsy:

There may be a genetic foundation for epilepsy, as certain gene mutations are linked to heightened seizure vulnerability. Genes that control ion channels, synaptic transmission, or neuronal excitability may be affected by these mutations. The following are some of the most well-known genetic epilepsy.

1.4.1.1 Dravet syndrome :

Mutations in the SCN1A gene, which codes for the voltage-gated sodium channel, result in Dravet syndrome. This mutation causes severe, drug-resistant seizures by disrupting neuronal excitability.

1.4.1.2 Genetic Generalized Epilepsies :

These epilepsy syndromes, which include juvenile myoclonic epilepsy, are associated with mutations in ion channel genes, such as those encoding sodium and potassium channels or GABA receptors.

1.4.1.3 Rett Syndrome:

Linked to mutations in the MECP2 gene, which impacts nervous system development and causes seizures as a component of the syndrome's clinical manifestation.

1.4.1.4 Focal Epilepsies:

These seizures are frequently associated with mutations in genes that control potassium and chloride channels, which are involved in synaptic transmission and neural communication. There may be a genetic foundation for epilepsy, as certain gene mutations are linked to heightened seizure vulnerability. (8)

1.4.2 Role of Pharmacogenomics in Precision Medicine:

Pharmacogenomics is the study of how an individual's genetic makeup influences their response to drugs. In the context of epilepsy, pharmacogenomics has become a crucial part of precision medicine.

Many patients with epilepsy have variations in their genetic code that affect the metabolism and efficacy of AEDs. For example, polymorphisms in genes encoding cytochrome P450 enzymes (e.g., CYP2C9 and CYP2C19) influence the metabolism of AEDs like carbamazepine and phenytoin. These genetic variations can affect the drug's absorption, distribution, and elimination, leading to variations in drug levels in the body and, consequently, treatment effectiveness and side effects.

For example, certain individuals may have slower metabolisms of various AEDs, which might result in hazardous drug concentrations and negative side effects. Some may metabolize medications too fast, leading to subtherapeutic doses that are ineffective in controlling seizures. To maximize therapeutic results and reduce side effects, physicians can choose the best medication and modify the dosage by detecting such genetic variants before beginning therapy.

1.4.3 Tailoring Treatment Based on Genetic Profile:

Treatment approaches for epilepsy can be tailored through the use of genetic testing. Clinicians can make better selections about which AEDs are likely to work best by detecting certain genetic mutations or polymorphisms in a patient's DNA. For instance.

1.4.4 SCN1A Mutations (Dravet Syndrome):

Patients who have Dravet syndrome, which is brought on by mutations in the SCN1A gene, usually react poorly to traditional AEDs such as carbamazepine or phenytoin. Nevertheless, more recent therapies like cannabidiol and stiripentol have demonstrated efficacy in controlling seizures in these individual.

1.4.5 KCNQ2 and KCNQ3 Mutations (Focal Epilepsies):

KCNQ2 and KCNQ3 genes encode potassium channels, and mutations in these genes have been associated with certain forms of focal epilepsy. By restoring appropriate potassium ion flow, potassium channel modulators like retigabine (sometimes referred to as Ezogabine) can assist these individuals manage their seizures.

1.4.6 GABA Receptor Mutations (Genetic Generalized Epilepsies):

Genes encoding GABA receptors have been linked to hereditary generalized epilepsies through mutations. For these people,

medications like valproate or topiramate that improve GABAergic transmission may be very helpful. Identifying individuals who are likely to respond well to these drugs can be aided by genetic testing.[8]

2.1 Biomarkers for Epilepsy:

A biomarker for epilepsy is a quantifiable aspect of the condition that enables the detection of epilepsy's presence, development, severity, and location.

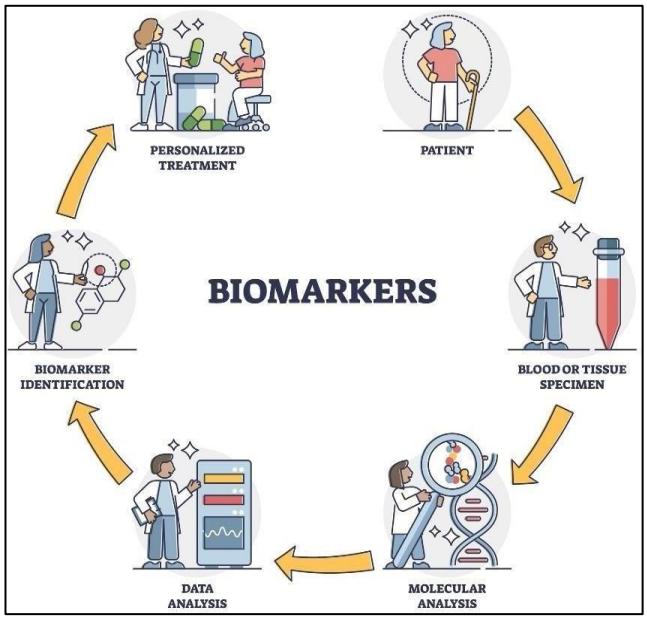

Figure 4: Biomarkers

2.1.1 Types of Biomarkers in Epilepsy :

The biomarkers that are important to and related to epilepsy come in a variety. These include biomarkers for neuroinflammation, microRNAs, microvascular damage, and structural and functional biomarkers.

2.1.1.1 Genetic Biomarkers:

The prognosis of disease, comprehension and prediction of therapy response, and assessment of antiepileptic drug adverse effects are all areas where genetic indicators have been found to be helpful. To far, over 900 genes have been shown to be connected to the onset and progression of epilepsy.

2.1.1.2 MicroRNAs(miRNAs):

Humans have over 1600 miRNAs, which control nearly half of all the genes that control proteins. Certain distinct miRNAs found in the human brain regulate dendritic shape, ion channel levels, neuronal migration, and glial function. Neurodegenerative diseases have been demonstrated to be caused by any changes in certain miRNAs.

2.1.1.3 Structural Biomarkers:

Certain structural alterations, such as axonal rearrangement, gliosis, segmental neuronal loss, or distinctive damage patterns, are frequently indicative of epilepsy, including chronic temporal lobe epilepsy. Diffusion tensor imaging, tractography, P magnetic resonance spectroscopy, H spectroscopy, and hippocampal MRI are examples of structural biomarkers used in rat models. Early identification of aberrant water movement by diffusion- weighted imaging enabled the early detection of epilepsy.(10)

3.1 3D Printing Technology:

One of the most innovative technologies in the pharmaceutical and healthcare industries is three-dimensional printing, which allows for the customization of dosages to meet the needs of each patient. This technology, also known as the "additive manufacturing technique," builds dosage forms in different sizes and shapes layer by layer to satisfy patient needs. Computed tomography (CT) and magnetic resonance imaging (MRI) are two examples of imaging techniques or computer-aided design software (CAD) that are used to generate 3D structures or patterns that meet drug dosage accuracy and precision.

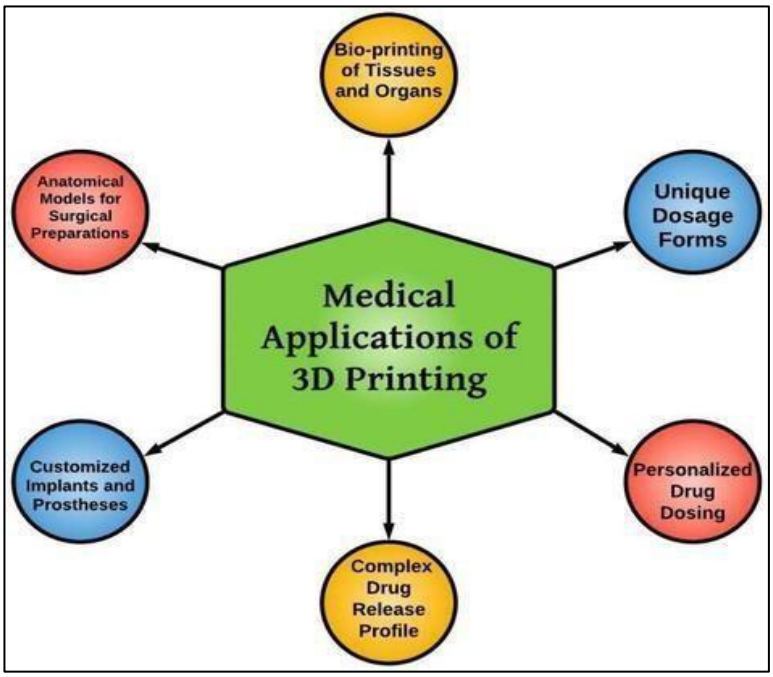

Figure 5: 3D Printing Technology

3.1.1 Classification of 3-D Printing Technology:

Generally speaking, 3D printing technology falls into seven categories:

1) Material jetting,
2) Material extrusion,
3) Binder jetting,
4) Powder bed fusion,
5) Sheet lamination,
6) Vat photopolymerization, and
7) Directed energy deposition.

3.2 Benefits of 3D printing technology:

1. **Flexible design:** Computer-aided design software makes it simple to create the more intricate drug combination designs.

2. **Rapid prototyping**: It makes it possible to manufacture parts in a matter of hours.

3. **Sustainability:** It gives dosage forms a great deal of strength and mechanical resistance, making it simple to combine different medications.

4. **Print on demand:** It offers the ability to fabricate doses on demand, requires less room for equipment installation, and requires less stock inventories.

5. **Fast design and production:** Rapid, highly reproducible, and precisely designed printed 3D items can be produced using computer-driven instructions.

6. **Minimal wastage:** There is relatively little waste material left behind after the procedure because there are very few ingredients needed and the end composition is liquid or semisolid.

7. **Cost effective:** The single-step procedure makes it extremely cost-effective because it uses fewer components, has fewer processing parameters, and takes less time.

8. **Environmentally friendly:** The equipment's lightweight components result in a low total fuel need for machine operation.

9. **Advanced healthcare:** The method may effectively print complex molecular structures, biological tissue, and organs in a customized dosage.(11)

3.3 3D Printed Drugs in Epilepsy:

Drugs that are 3D printed could greatly enhance the treatment of complicated illnesses that call for individualized care. The chronic condition known as epilepsy is typified by aberrant brain electrical activity that results in recurrent seizures. Its clinical symptoms can vary widely. Anti-seizure drugs with set dosages are the primary treatment for epilepsy (ASMs).By lowering brain electrical activity, ASMs lessen seizure frequency and severity. Because of its large therapeutic index, dependable pharmacokinetics, and low medication interactions, LEV is becoming more and more important in precision medicine for epilepsy and is positioned as a viable alternative for individualized treatment plans. Patients with epilepsy may benefit from individualized care thanks to 3D-printed medications.

A pharmaceutical company called Aprecia Pharmaceuticals produced 3D-printed tablets called Spritam on a commercial scale using a patented BJP platform called ZipDose Technology. On August 3, 2015, Spritam was approved by the US Food and Drug Administration (FDA).The distinctive delivery system of 3D-printed Spritam and the advantageous pharmacokinetics of LEV contribute to more individualized methods to epileptic therapy.(12)

Figure 6:First 3D Printed-Levetiracetam

3.4 Epilepsy: complex disease and treatment:

Since its start in the 1960s, our knowledge of the pathophysiology of seizure types and epilepsy subtypes has changed, leading to ongoing updates to seizure and epilepsy classifications based on scientific advancements. Three levels make up the most recent classification of epilepsy: the first level categorizes the disease's symptoms by type by defining the kind and onset of seizures, which

can be focal or generalized. The disease (i.e., the epilepsy type) is classified at the second level, which mirrors the first classification based on the predominant seizure type. The diagnosis of epilepsy syndrome, a distinctive cluster of seizure types, clinical and EEG features, and specific etiological findings structural, genetic, infectious, metabolic, immune, or of unknown etiology is made at the third level.

Seizures and aberrant neurocognitive development are hallmarks of a broad and diverse set of rare, debilitating, and mainly incurable neurodevelopmental illnesses known as developmental and epileptic encephalopathies (DEEs).More than 250 DEEs exist, and the number is still rising. One well-known DEE is Dravet syndrome (DS), which is 80% of the time caused by a haploinsufficiency (loss-of-function) mutation in one copy of the SCN1A gene, which codes for the alpha subunit of the voltage-gated sodium channel Nav1.1. tuberous sclerosis complex (TSC), an autosomal dominant disorder that, in 70% of cases, is brought on by mutations in TSC1 or TSC2 and causes benign (non-cancerous) tumors in the brain and other body organs ; and (iii) Lennox-Gastaut syndrome (LGS), which has a variety of causes, many of which are not genetic.

The scientific community recently renamed "antiepileptic drugs" (AEDs) as "antiseizure medications" (ASMs) due to the fact that the treatments primarily treat symptoms and have no effect on comorbidities or the disease's underlying causes. ASMs can be divided into four major kinds based on their mechanism of action (MOA).

(1) voltage-gated ion channel modulators, such as sodium, calcium, and potassium channels;

(2) GABA-mediated inhibition enhancers that engage GABAA receptors, the GABA transporter (GAT1), glutamic acid decarboxylase (GAD), or GABA-metabolizing enzyme GABA aminotransaminase (GABA-T);

(3) inhibitors of ionotropic glutamate receptor-mediated synaptic excitation, such as α-amino-3-hydroxy-5-methyl-4-isoxazole-propionate (AMPA) receptors;

(4) modulators of synaptic neurotransmitter release, which target the presynaptic release machinery, such as the α2δ subunit of voltage-gated calcium channels and synaptic vesicle protein 2A (SV2A).

Treatment choices should ideally be guided by an accurate diagnosis and categorization of the epilepsies, and the classification of the illness should take treatment response into account. Nevertheless, there are currently relatively few treatments that are unique to a diagnostic or ictogenic process. Correct diagnosis for the great majority of epileptic syndromes, at most, results in the avoidance of certain ASMs that are known to worsen seizures in a certain syndrome, such as carbamazepine and ASMs with a similar mechanism of action for DS or idiopathic generalized epilepsies.(4)

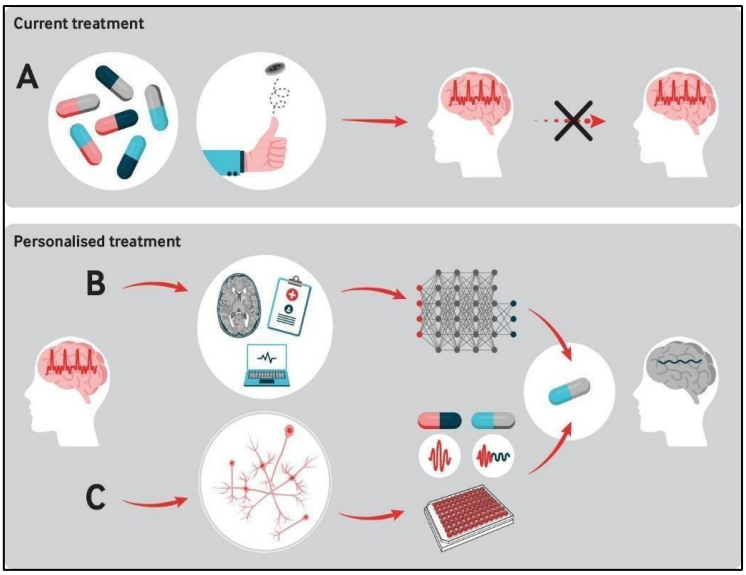

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Figure 7: Personalised treatment

3.5 Modern Approaches for Treatment:

GABA activation, glutamate receptor inhibition, and voltage-dependent ion channel modulation are the major mechanisms by which approved AEDs for the treatment of epilepsy operate. Numerous researchers have found a number of promising therapeutic targets and pathways, some of which are presented below, including ones that are shared with neurodegenerative illnesses.

3.5.1 MTOR Pathway

Cell development, proliferation, differentiation, and metabolism in the brain are all regulated by rapamycin, which targets this signaling system in mammals. Numerous investigations have demonstrated that acquired forms of epilepsy, including temporal lobe epilepsy, are caused by dysregulation of mTOR. Consequently, the development of more tolerated anti-epileptic and anti-epileptogenic medications may result from therapeutic involvement in this route.

3.5.2 Pathways:

There is evidence from a number of studies and investigations that suggests the basis of seizures and the process of epileptogenesis are linked to inflammatory mediators generated by peripheral immune cells and brain cells. Changes in the inflammatory and immunological pathways may be the cause and result of the many forms of epilepsy, according to data and facts that have surfaced.

3.5.3 Breakdown of Blood-Brain Barrier:

Regardless of their cause, epileptogenic brain injuries are characterized by blood- brain barrier disruption. Any damage to the blood-brain barrier microvasculature during brain injury causes serum albumin to leak into the cerebral cortex's microenvironment. This triggers a signaling cascade in astrocytes, which activates the transforming growth factor β receptor (TGFβR) and causes local inflammation. When astrocytes malfunction, the extracellular brain environment's equilibrium is compromised, which in turn causes the neurons to become more excitable. One intriguing new target that disrupts the epileptogenesis pathway is TGFβR. This is because TGFβ signaling in the albumin is blocked, which reverses the transcriptional changes and inflammation associated with activated glia and stops epileptogenesis from progressing. (6)

4.1 Role of AI and Digital Health:

4.1.1 AI applications in epilepsy diagnostics:

Automated EEG analysis: With AI-powered automated EEG analysis, epilepsy diagnostics have advanced significantly, allowing for faster and more accurate seizure pattern recognition. EEG data analysis frequently employs support vector machines (SVMs) and convolutional neural networks (CNNs), each of which has special advantages in identifying the intricate patterns linked to epileptic activity. CNNs are particularly good at finding spatial patterns in EEG signals, but SVMs are better at processing high-dimensional data and are resistant to overfitting, which is important for medical applications. By swiftly analyzing large volumes of EEG data, these models help physicians diagnose patients more rapidly and enhance seizure monitoring, particularly for patients who need continuous, real-time monitoring.

Advanced AI systems for epilepsy include models like SCORE-AI (Standardized Computer-based Organized Reporting of EEG) and SPaRCNet (Seizure Prediction and Reliable Control Network). While SCORE-AI provides a consistent system for reporting EEG results, increasing consistency and accuracy across diagnostic settings, SPaRCNet has demonstrated promise in predicting seizure start with great sensitivity. These models do have some drawbacks, though. Although SPaRCNet works effectively in controlled settings, a variety of real-world clinical circumstances can cause it to lose sensitivity. Despite its advantages, SCORE-AI occasionally generates false positives, which may result in needless therapy modifications.

4.1.1.1 AI for functional imaging (MRI, PET):

AI has also shown great promise in identifying epileptogenic Zones the parts of the brain that cause seizures by evaluating functional imaging data from tests like MRIs and PET scans. High-resolution imaging data can be processed especially well by deep learning models like CNNs and autoencoders, which can detect minute anomalies that are challenging for doctors to manually spot. Hippocampal sclerosis, cortical dysplasia, and other structural brain abnormalities linked to epilepsy, for instance, can be detected by AI models trained on massive amounts of MRI data. Traditional visual analysis frequently misses these conditions. Artificial intelligence (AI)-driven methods have a number of benefits over conventional imaging methods. Conventional approaches depend

on radiologists' and neurologists' subjective manual interpretation, which is impacted by their experience. Conversely, AI models can swiftly evaluate thousands of photos and produce reliable, impartial evaluations that help identify epileptogenic zones more precisely. AI models that analyzed MRI data in clinical trials produced diagnostic accuracy rates ranging from 75% to 90%, which was far higher than the usual accuracy rates of manual interpretation alone. AI's dependence on huge, high-quality datasets for training is a drawback, too, as differences in patient populations, imaging techniques, and scanner quality can impact model performance.

4.1.1.2 Comparison with traditional diagnostic Methods:

Combining the advantages of automated pattern recognition with traditional expert interpretation, AI enhances diagnosis accuracy when used in conjunction with conventional diagnostic techniques such as EEG, MRI, and PET. Traditional techniques of diagnosing epilepsy can be affected by a number of circumstances, such as the availability of modern imaging technologies, the length and quality of EEG monitoring, and the experience of the clinician. The reliability of diagnostic results is increased by AI algorithms, which methodically examine EEG and imaging data to find patterns that humans would miss. Research contrasting AI-enhanced EEG and imaging with conventional diagnostics shows that AI increases overall diagnostic sensitivity, particularly when unusual presentations are present. For example, compared to traditional EEG analysis alone, AI- integrated systems can enhance seizure detection rates by 20–30%, making them a useful tool for complex cases or situations with limited expert resources [70–75]. Notwithstanding these benefits, data generalization is a problem for AI models since models developed on a single dataset might not function reliably across various patient demographics or clinical contexts. Furthermore, the "black box" character of many AI models where decision-making procedures are not entirely transparent can impede uptake and clinician trust.

4.1.1.3 Limitations of AI diagnostics:

Access to sizable, varied datasets for training and validation is essential to the efficacy of AI diagnosis in epilepsy. However, because different institutions have different equipment, EEG and imaging techniques, and population demographics, collecting this kind of data is difficult. Furthermore, the intricacy of certain AI models leads to "black box" problems, in which the models' internal decision-making processes cannot be fully understood. Clinicians may find it challenging to evaluate AI suggestions due to this lack of transparency, which also raises ethical concerns about responsibility in cases of misdiagnosis. Finally, applying AI models to patient populations or surroundings that differ from those in the training data may result in a decline in model performance, making it difficult to generalize these models across a variety of clinical situations.(9)

4.1.2 AI in epilepsy treatment and management:

4.1.2.1 AI-driven personalized Treatments:

AI has the potential to greatly influence epilepsy therapy in the vital field of personalized medicine by tailoring anti-seizure medication (ASM) regimens to the requirements of specific individuals. In traditional ASM selection, patients frequently go through a trial-and-error approach, cycling through different medications and dosages in an attempt to discover a good regimen. This can be a time-consuming and frustrating procedure. Large sets of patient-specific data, including as genetic information, seizure history, and therapy reactions, are analyzed by AI models to determine the best ASM regimen for a given person. AI can use this data to assist physicians in making better decisions, which will eliminate the need for repeated treatments that involve trial and error. The findings of predictive models have been encouraging. For example, machine learning systems that have been trained on clinical data and genetic markers have shown up to 70–80% accuracy rates in predicting the efficacy of ASM for particular patient profiles. To guarantee accurate predictions and that algorithms don't add biases based on insufficient or skewed datasets, clinical practice implementation of these models necessitates strict regulatory control.

4.1.2.2 Regulatory Guidelines:

Guidelines for AI and machine learning in healthcare, particularly with regard to instruments meant for direct clinical use, have been introduced by the FDA. Before AI-based therapy models for epilepsy can be used in patient care, the FDA mandates that they adhere to strict safety, efficacy, and transparency guidelines. These recommendations place a strong emphasis on patient safety, model interpretability, and real-world validation all of which are vital in high-stakes situations like treating epilepsy. Furthermore, it is advised that AI models be continuously monitored and updated to guarantee that prediction tools continue to be accurate as new data becomes available.

4.1.2.3 Responsive neurostimulation (RNS):

An inventive use of AI in the treatment of epilepsy, especially for those with drug- resistant epilepsy, is represented by responsive neurostimulation (RNS) devices. Implantable RNS devices, like the Neuro Pace RNS System, provide electrical stimulation to stop seizure activity and track brain activity in real time. By examining EEG data to detect seizure beginning patterns, artificial intelligence (AI) improves these systems and allows the gadget to deliver prompt therapies that could stop seizure progression.(43). RNS devices have been shown in recent studies to be successful in lowering seizure frequency in individuals with refractory epilepsy; some patients have had seizure reductions of up to 50%. However, patient-specific seizure patterns and the requirement for exact device programming which frequently necessitates ongoing adjustments can restrict the effectiveness of RNS devices. Because RNS devices are intrusive and need to be implanted surgically, regulatory approvals emphasize the significance of long-term safety data. Furthermore, RNS systems' expense and intricacy may restrict their usability, posing real obstacles to their broad adoption.

4.1.2.4 Predicting drug Responses:

Additionally, considering that about one-third of epileptic patients are resistant to routinely used drugs, AI may be able to predict each patient's unique reaction to ASMs. AI models can predict a patient's response to particular ASMs by examining genetic information, clinical history, and seizure characteristics. This might potentially cut down on the time and expense spent on useless therapies. This method is in line with precision medicine since it tailors care to the particular biological and clinical characteristics of each patient. Data heterogeneity and the requirement for ongoing validation as new genetic and clinical data become available are obstacles in predictive modeling for ASM response. Drug metabolism and efficacy, for example, are significantly influenced by patient genetics; nevertheless, the complete spectrum of genetic variability across various populations may not be fully captured by current datasets. Predictive models must therefore be updated frequently to guarantee that they continue to be accurate and relevant for larger patient populations. The requirement for flexible models that can be adjusted to specific healthcare settings is further highlighted by the fact that variations in medication compositions and treatment methods throughout institutions might make model generalization even more difficult.

4.1.2.5 Challenges in predictive Modeling:

Despite its enormous potential, predictive modeling has a number of logistical and technical challenges. One of the main challenges is data heterogeneity, or the variance in data types and sources. Inconsistencies in the various datasets that AI models rely on, which include demographic, clinical, and genetic data, can reduce the accuracy of the models. For example, it can be challenging for a single model to generalize across multiple population since genetic markers can differ among ethnic groups. In a similar vein, models developed in one clinical setting might not function as effectively in another where patient demographics and treatment regimens vary. The requirement for ongoing validation and recalibration presents another difficulty. Because they are dynamic, predictive models need to be regularly updated with fresh patient data in order to remain accurate. In order to compile high-quality data, this continuous validation necessitates cooperation between institutions and is resource- intensive. Additionally, ethical monitoring is required as predictive models become more integrated into treatment planning to guarantee that patient-centered decisions are maintained and that AI forecasts do not unintentionally reinforce biases or worsen healthcare inequities.

4.2 Future Directions:

4.2.1 AI in Personalized Medicine:

In order to guarantee patient safety, accountability, and equity, ethical and regulatory frameworks must develop in tandem with AI technologies. Guidelines for AI applications in healthcare are being established by regulatory agencies such as the FDA; nevertheless, to create comprehensive standards for AI in epilepsy, neurologists, data scientists, and legislators must continue to collaborate. Model generalizability, the creation of interpretable AI systems, and the integration of multimodal data from wearables, imaging, and genetics should be the top priorities of future research. The field of epilepsy treatment may fully utilize AI to deliver safer, more efficient, and individualized patient care by developing these areas and addressing ethical and regulatory issues. AI-driven epilepsy treatment may go from theory to reality with interdisciplinary collaboration, providing a significant influence on patient results and quality of life. (9)

4.2.2 Emerging Technologies for 3D-Printed Drugs:

3D printing is being investigated for new medications and therapies. The medications T19, T20, and T21 were created by the Chinese pharmaceutical company Triastek (Nanjing, China) via a unique 3D-printing technology called MELT® (Melt Extrusion Deposition).

This technique is a specific kind of FDM that provides additional control over the distribution and geometry of excipients and APIs. This makes it possible to create multi-compartment medications with intricate release profiles, which makes it possible to produce customized drug formulations on a wide scale.

One new development in the field that is still undergoing extensive research is four- dimensional (4D) printing. The term "4D printing" describes the application of 3D printing technology to the development of drug delivery systems that are capable of changing their properties, structure, or shape over time in response to external stimuli. Since the printed structures are intended to change or evolve after printing in order to enhance medication release or targeting, time serves as the "fourth dimension" in this context.

AI applications have the potential to revolutionize 3D medication manufacture and design. In order to improve accuracy, consistency, and personalization, formulation design and drug release profiles may be optimized thanks to AI algorithms' capacity to evaluate vast databases of drug properties, patient clinical factors, and printing settings. Thus, we can get closer to providing customized, on-demand therapies with increased speed, safety, and scalability by fusing AI with 3D printing.(12)

5.1 MANAGEMENT OF DRUGS:

Drug Name	Formulation Types	Typical Dosage Range	References
Carbamazepine	Tablets (IR, ER), suspension	Initial: 100–200 mg twice daily; Max: 1200 mg/day	13
Lamotrigine	Tablets (IR, ER), chewable, dispersible	Initial: 25 mg daily (monotherapy); Max: 400 mg/day (monotherapy)	13
Valproic Acid	Tablets (IR, ER), syrup, injection	Initial: 10–15 mg/kg/day; Max: 60 mg/kg/day	13
Levetiracetam	Tablets, oral solution, injection	Initial: 250 mg twice daily; Max: 3000 mg/day	13
Brivaracetam	Tablets, oral solution, injection	Initial: 50 mg twice daily; Max: 200 mg/day	13
Perampanel	Tablets, oral suspension	Initial: 2 mg nightly; Max: 12 mg/day	13
Clobazam	Tablets, oral film, oral suspension	Initial: 5–10 mg/day; Max: 40 mg/day	14
Clonazepam	Tablets, wafer	Initial: 0.5 mg twice daily; Max: 20 mg/day	13
Cenobamate	Tablets	Initial: 12.5–25 mg/day; Max: 200 mg/day	13
Topiramate	Tablets, sprinkle capsules	Initial: 25 mg once/twice daily; Max: 500–800 mg/day	13
Gabapentin	Capsules, tablets	Initial: 100 mg three times daily; Max: 2400 mg/day	13
Ethosuximide	Capsule, syrup	Initial: 250 mg twice daily; Max: 1000 mg/day	13
Cannabidiol	Oral solution (Epidiolex)	Initial: 2.5 mg/kg twice daily; Max: 10 mg/kg twice daily	13
Diazepam	Tablets, rectal gel, injection	Initial: 2–10 mg two to four times daily; Max: 40 mg/day	13
Lorazepam	Tablets, injection	Initial: 1–2 mg two to three times daily; Max: 10 mg/day	13

CONCLUSION:

Personalized medicine represents a transformative shift in the management of epilepsy, offering a patient-centered approach that integrates genetic, molecular, and clinical data to optimize treatment outcomes. Through the use of pharmacogenomics, clinicians can now identify genetic variants that influence drug response, thereby minimizing adverse effects and enhancing therapeutic efficacy. The identification of biomarkers has further improved diagnostic accuracy and treatment monitoring, enabling the prediction of disease progression and response to antiepileptic drugs.

The emergence of advanced technologies such as 3D printing has introduced innovative solutions for individualized drug formulation, ensuring precise dosing and improved patient compliance. Likewise, the integration of artificial intelligence and digital health tools has enhanced diagnostic precision, seizure prediction, and real time treatment adjustment, marking a significant step toward precision-based neurology.

Although challenges remain such as ethical concerns, data standardization, and regulatory requirements the potential of combining genomics, AI, and smart drug delivery systems holds immense promise. As research advances, personalized approaches will likely redefine epilepsy management, shifting the focus from generalized therapy to tailored interventions that improve quality of life and long-term outcomes for patients worldwide.

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How to cite this article:
Karthick M et al. Ijppr.Human, 2026; Vol. 32 (3):211-224.

Conflict of Interest Statement: All authors have nothing else to disclose.