Brain Disorders 19 (2025) 100261

Contents lists available at ScienceDirect

Brain Disorders

journal homepage: www.sciencedirect.com/journal/brain-disorders

A review of neuroimaging in epilepsy: Diagnostic strategies and clinical decision framework

Bright Worlanyo Aklamanu

Graduate School of Nuclear and Allied Science, Department of Medical Physics, University of Ghana, Atomic Campus. P. O. Box AE 1, Accra. Ghana

ARTICLE INFO

Keywords:
Epilepsy
Neuroimaging
Clinical decision-making
Low- and Middle-Income Countries (LMICs)

ABSTRACT

Epilepsy, a chronic neurological disorder characterized by recurrent unprovoked seizures, demands precise diagnostic imaging. This review critically examines both structural and functional neuroimaging modalities MRI, CT, PET, SPECT, MEG, fMRI, MRS, DTI, and ASL in terms of diagnostic accuracy, patient comfort, cost-effectiveness, and accessibility. Structural MRI continues to serve as the cornerstone of epilepsy imaging, while functional and metabolic techniques offer vital insights in MRI-negative or drug-resistant cases. A clinical decision-making framework is proposed, guiding imaging selection based on seizure presentation and resource context. The review also addresses the implementation challenges in low- and middle-income countries (LMICs), including infrastructure limitations, economic barriers, and workforce shortages, while offering feasible strategies to improve access. Emphasis is placed on the integration of multimodal imaging and the development of context-sensitive, tiered approaches to optimize epilepsy care globally.

1. Introduction

Epilepsy represents one of the most prevalent neurological disorders worldwide, affecting approximately 50 million individuals globally, with an annual incidence of 2.4 million new cases [1]. The accurate diagnosis, localization, and characterization of epileptogenic foci remain critical challenges in clinical practice, directly influencing treatment decisions and patient outcomes. Magnetic Resonance Imaging (MRI) has established itself as the cornerstone imaging modality for evaluating patients with epilepsy, offering unparalleled soft tissue contrast and multiparametric capabilities without ionizing radiation exposure [2]. The evolution from standard 1.5T to high-field (3T) and ultra-high-field (7T) systems has dramatically improved the detection sensitivity for subtle epileptogenic lesions, particularly focal cortical dysplasias, hippocampal sclerosis, and vascular malformations that were previously classified as "MRI-negative" epilepsies [3].

In contrast, computed tomography (CT) remains a vital tool in emergency settings for rapid assessment of acute seizures, particularly to rule out hemorrhage or mass effect. However, its sensitivity is limited for chronic or non-hemorrhagic epileptogenic lesions [4]. Functional imaging strategies including positron emission tomography (PET), single-photon emission computed tomography (SPECT), magnetoencephalography (MEG), and advanced MRI techniques such as arterial spin labeling (ASL), diffusion tensor imaging (DTI), functional MRI (fMRI), and magnetic resonance spectroscopy (MRS) complement structural imaging by providing metabolic and perfusion data essential for presurgical evaluation [5].

Recent literature reviews have begun to address the comparative value of different neuroimaging approaches in neurological disorders. For instance, a recent study conducted a comprehensive overview of MRI and MRS techniques in epilepsy, focusing on their clinical applications and technological advancements [6]. In a broader context, a comparative analysis of traditional and modern imaging techniques across various neurological disorders was also conducted, evaluating diagnostic performance and examining the synergistic potential of hybrid imaging approaches such as PET/CT and PET/MRI [7]. While these contributions have significantly advanced our understanding of neuroimaging applications, the current review distinguishes itself in several fundamental ways.

Unlike previous studies [6] who primarily focused on MR-based techniques, and explored imaging across the spectrum of neurological disorders, [7] this review specifically addresses the comparative utility of MRI and alternative strategies exclusively in epilepsy. Also, the review extends beyond previous works by incorporating a detailed comparative analysis not only in terms of diagnostic accuracy but also considering factors such as cost-effectiveness, patient comfort, accessibility, and time efficiency of various imaging strategies. Importantly, this review introduces a clinical decision-making framework that

---

E-mail address: aklamanub@gmail.com.

https://doi.org/10.1016/j.dscb.2025.100261

integrates these factors to guide imaging modality selection in the context of epilepsy. This added dimension enhances the practical relevance of the analysis, enabling clinicians to make context-sensitive imaging choices aligned with both diagnostic needs and healthcare system constraints. This disease-specific and decision-oriented approach provides a more granular and clinically actionable evaluation of neuroimaging technologies in epilepsy care.

2. Neuroimaging strategies in epilepsy

Neuroimaging plays a pivotal role in diagnosing, managing, and understanding neurological disorders, particularly in cases of medically refractory epilepsy. Advances in structural and functional imaging techniques have enhanced localization of epileptogenic zones, improved surgical outcomes, and provided insights into network-level abnormalities. Below is a synthesis of key strategies and innovations in this field.

2.1. Structural neuroimaging

2.1.1. Overview

Structural neuroimaging refers to techniques that visualize the anatomical features of the brain, allowing for the detection of structural abnormalities that may be associated with neurological disorders, including epilepsy[8]. Unlike functional neuroimaging, which measures brain activity, structural imaging provides detailed information about brain morphology, tissue composition, and pathological changes [9].

2.1.2. Modalities of structural neuroimaging

2.1.2.1. Magnetic resonance imaging (MRI). MRI has emerged as the gold standard for structural imaging in epilepsy due to its excellent soft tissue contrast, multiplanar capabilities, and lack of radiation exposure [10]. Various MRI sequences provide complementary information about brain structure. T1-weighted imaging provides excellent anatomical detail and is useful for identifying developmental malformations and volumetric abnormalities [11]. T2-weighted imaging is particularly sensitive to tissue water content, making it valuable for detecting edema, inflammation, and certain pathologies such as hippocampal sclerosis. Fluid-Attenuated Inversion Recovery (FLAIR) suppresses cerebrospinal fluid signal, enhancing the visibility of periventricular and cortical lesions, particularly helpful in detecting focal cortical dysplasias and subtle signal changes [12].

Diffusion-weighted imaging (DWI) measures the diffusion of water molecules in brain tissue, useful for identifying acute ischemic changes and certain inflammatory conditions[13]. Susceptibility-weighted imaging (SWI) is highly sensitive to blood products and calcium, valuable for detecting vascular malformations, microbleeds, and calcifications that may cause seizures. Double Inversion Recovery (DIR) suppresses signals from both white matter and cerebrospinal fluid, improving the detection of cortical and subcortical lesions [14].

Advances in MRI technology have led to the development of high-field (3 Tesla) and ultra-high-field (7 Tesla and above) scanners that offer several advantages over conventional 1.5 Tesla systems. These advantages include improved signal-to-noise ratio, enhanced spatial resolution, superior lesion detection (particularly for subtle cortical dysplasias), better characterization of hippocampal subfields, and more accurate delineation of subtle structural abnormalities. Studies have demonstrated that high-field MRI can detect epileptogenic lesions in 20–30 % of patients previously classified as having "non-lesional" epilepsy based on standard 1.5T imaging [15].

2.1.2.2. Computed tomography (CT). While MRI is preferred for most epilepsy evaluations, CT maintains an important role in specific clinical scenarios. CT is valuable in emergency settings for acute seizure presentations, rapid screening for gross abnormalities such as hemorrhage, large tumors, or hydrocephalus, detection of calcifications (e.g., tuberous sclerosis, neurocysticercosis), evaluation of patients with MRI contraindications (e.g., certain implanted devices), and assessment of skull abnormalities and fractures [16]. CT is more widely available and faster than MRI, making it valuable in acute settings despite its inferior soft tissue contrast and exposure to ionizing radiation.

2.1.2.3. Specialized structural imaging techniques. Several advanced MRI techniques provide additional structural information relevant to epilepsy. Volumetric MRI with three-dimensional acquisition allows for quantitative assessment of brain structures, particularly useful for evaluating hippocampal volumes in temporal lobe epilepsy[17]. Diffusion Tensor Imaging (DTI) maps the diffusion of water molecules along white matter tracts, enabling the visualization of structural connectivity [18]. DTI can identify subtle white matter abnormalities and help plan surgical trajectories to minimize disruption of critical pathways.

MR Spectroscopy (MRS), while primarily a metabolic imaging technique, provides structural information at the molecular level by detecting altered metabolite concentrations in epileptogenic zones (e.g., reduced N-acetylaspartate as a marker of neuronal loss)[19]. Quantitative MRI techniques measure specific tissue properties (T1/T2 relaxation times, proton density) to detect subtle abnormalities not visible on conventional imaging[11]. Voxel-Based Morphometry is an automated analysis technique for detecting subtle regional differences in gray or white matter density or volume. Cortical Thickness Analysis provides a quantitative method to measure thickness of the cerebral cortex, helpful in identifying subtle cortical malformations [20].

2.1.3. Diagnostic accuracy of structural neuroimaging

Structural MRI remains the gold standard for detecting anatomical abnormalities such as hippocampal sclerosis, cortical dysplasias, tumors, and vascular malformations, boasting a high sensitivity of 85–95 % in lesional epilepsy [21]. In mesial temporal sclerosis, high-resolution MRI demonstrates superior sensitivity (97 %) for detecting hippocampal atrophy and hyperintensity on FLAIR sequences[22], while focal cortical dysplasia benefits from volumetric MRI analysis to identify subtle cortical malformations, such as gray-white matter junction blurring [5]. For tumors, contrast-enhanced MRI provides detailed characterization of lesion morphology and vasculature, though computed tomography (CT) remains critical in acute settings to rapidly exclude hemorrhage or mass effect [23]. Additionally, susceptibility-weighted imaging (SWI) is valuable for detecting cavernous and other vascular malformations, as well as microbleeds associated with remote trauma. Vascular malformations, including cavernomas and arteriovenous malformations (AVMs), are optimally visualized through MRI and MR angiography (MRA), while CT angiography serves as a pragmatic alternative for acute hemorrhage evaluation [24]. Computed tomography (CT) offers rapid, widely available imaging, useful for detecting calcifications, hemorrhages, and certain malformations. However, its sensitivity for subtle epileptogenic lesions is low (30–40 %), and it involves radiation exposure, which may limit its use, especially in children [15]. Table 1 provides a summary of structural imaging techniques, key features, diagnostic value and practical considerations.

2.2. Functional and metabolic imaging

2.2.1. Overview

Functional and metabolic neuroimaging encompasses a diverse array of techniques designed to visualize and quantify neural activity and biochemical processes in the brain [25]. Unlike structural imaging, which primarily depicts anatomical abnormalities, functional neuroimaging captures the dynamic aspects of brain function, including regional cerebral blood flow, glucose metabolism, receptor binding, and electrophysiological activity[26]. This dynamic perspective is particularly valuable in epilepsy, where epileptogenic networks often extend

Table 1
Structural Imaging Techniques.

Modality	Key Features	Diagnostic Value	Practical Considerations
Structural MRI	High-resolution anatomical imaging	• Gold standard (85–95 % sensitivity for lesional epilepsy) • Detects hippocampal sclerosis, cortical dysplasias, tumors	• 30–60 min scan time • High cost but justified by yield • Limited by implants and claustrophobia
CT Scan	X-ray based cross-sectional imaging	• Limited sensitivity (30–40 %) • Good for calcifications, hemorrhage, bone abnormalities	• Quick (5–10 min) • Lower cost than MRI • Widely available • Involves radiation exposure
7T Ultra-High Field MRI	Higher resolution MRI	• Superior detection of subtle abnormalities • 10–20 % higher lesion detection than standard MRI	• Very limited availability • Very high cost • Similar scan time to MRI • safety concerns in patients with implants; increased acoustic noise and risk of vertigo or dizziness may affect tolerance

beyond visible structural lesions or may exist in the absence of any detectable structural abnormality

2.2.2. *Key functional and metabolic neuroimaging modalities*

This section describes techniques that go beyond anatomy to examine brain function. The progression from fMRI to PET, SPECT, and MEG represents increasing specificity for epileptogenic foci but also growing complexity and limited availability. These modalities are particularly valuable when structural imaging is normal but clinical signs strongly suggest epilepsy. Table 2 effectively illustrates how these techniques complement structural imaging rather than replace it.

2.2.2.1. Positron emission tomography (PET). PET imaging employs radioactively labeled compounds (radiotracers) to visualize metabolic processes in the brain [27]. The most commonly used radiotracer in epilepsy is fluorodeoxyglucose (FDG), which measures regional glucose metabolism [28]. During interictal periods (between seizures), epileptogenic zones typically exhibit hypometabolism, presenting as areas of reduced FDG uptake [29]. This characteristic makes FDG-PET particularly valuable in localizing epileptogenic zones, especially in cases where MRI findings are negative or inconclusive. Beyond glucose metabolism, newer PET radiotracers targeting neurotransmitter systems, such as serotonin, dopamine, and gamma-aminobutyric acid (GABA), have emerged, offering insights into the neurochemical basis of epileptogenesis [30].

2.2.2.2. Single photon emission computed tomography (SPECT). SPECT utilizes gamma-emitting radiotracers to measure regional cerebral blood flow, which serves as an indirect marker of neuronal activity [31]. Unlike PET, SPECT radiopharmaceuticals have longer half-lives, making them more practically applicable in clinical settings. The unique advantage of SPECT in epilepsy lies in its ability to capture blood flow changes during different phases of seizure activity [32]. Interictal SPECT typically reveals hypoperfusion in epileptogenic zones, while ictal SPECT (performed during seizures) demonstrates hyperperfusion in the seizure onset zone [33]. Subtraction ictal SPECT coregistered to MRI (SISCOM) further enhances the utility of this technique by highlighting differences between ictal and interictal perfusion patterns, thereby improving the localization of seizure foci [34].

2.2.2.3. Functional magnetic resonance imaging (fMRI). fMRI measures brain activity by detecting changes in blood oxygenation level-dependent (BOLD) contrast, which reflects the dynamic coupling between neuronal activity and cerebral blood flow [35]. Task-based fMRI protocols can identify eloquent cortical areas (responsible for critical functions such as language, memory, and motor control) in relation to epileptogenic zones, thereby guiding surgical decision-making to minimize postoperative functional deficits. Resting-state fMRI, which examines intrinsic brain connectivity during rest, has revealed alterations in functional networks in epilepsy, suggesting that seizure epilepsy involve network-level disruptions rather than isolated focal abnormalities [36]. Simultaneous EEG-fMRI recordings provide complementary

Table 2
Functional & Metabolic Imaging Techniques.

Modality	Key Features	Diagnostic Value	Practical Considerations
Functional MRI (fMRI)	Maps brain activity via hemodynamics changes	• 70–90 % concordance with invasive methods • Valuable for presurgical cognitive mapping	• 45–90 min procedure • imited to specialized centers • Requires patient cooperation with tasks
PET Scan	Measures glucose metabolism	• 70–85 % sensitivity • Especially useful with negative MRI	• 20–40 min scan + 30–60 min uptake • Limited availability • High cost • Requires radiotracer
SPECT	Measures regional cerebral blood flow	• Ictal: 90 % sensitivity • Interictal: 50–70 % sensitivity	• 15–30 min scan • Requires radiotracer • Ictal studies need precise timing
Magnetoencephalography (MEG)	Records magnetic fields from neural activity	• 80–90 % sensitivity for epileptiform activity • Excellent for neocortical sources	• 1–2 hour recording • Very high cost • Extremely limited availability
MR Spectroscopy (MRS)	Measures brain metabolites	• 60–70 % sensitivity • Detects metabolic changes (esp. NAA reduction)	• Adds 15–20 min to MRI • Moderate additional cost
Arterial Spin Labeling (ASL)	Measures blood flow without contrast	• 60–75 % sensitivity for perfusion abnormalities	• Adds 5–10 min to MRI<b • No contrast needed • Limited availability
EEG-fMRI	Combined electrical and hemodynamic imaging	• 80–90 % specificity for epileptogenic networks • Valuable in non-lesional epilepsy	• 60–90 min procedure • Research centers only • Specialized analysis required
High-Density EEG (HD-EEG)	Multi-channel EEG (64–256 electrodes)	High spatial resolution for epileptogenic zone localization	Moderate cost; requires skilled operators and advanced analytic software

information by correlating hemodynamic responses with electrophysiological events, offering insights into the generators of interictal epileptiform discharges[37].

2.2.2.4. Magnetic resonance spectroscopy (MRS). MRS provides noninvasive measurements of brain metabolites, including N-acetylaspartate (NAA, a marker of neuronal integrity), choline (reflecting membrane turnover), creatine (an energy metabolite), and neurotransmitters such as GABA and glutamate [38]. In epilepsy, the epileptogenic zones often exhibit decreased NAA levels, indicating neuronal dysfunction or loss, and alterations in excitatory and inhibitory neurotransmitter concentrations [39]. These metabolic signatures can help identify the epileptogenic substrate, particularly in cases where conventional structural imaging appears normal.

2.2.2.5. Arterial spin labeling (ASL) perfusion MRI. ASL is a non-contrast MRI technique that quantifies cerebral blood flow by magnetically labeling arterial blood water as an endogenous tracer [40]. In epilepsy, ASL can detect perfusion abnormalities in the epileptogenic zone, typically showing hypoperfusion interictally and hyperperfusion ictally [41]. While it offers lower temporal resolution compared to SPECT, its advantages include non-invasiveness, absence of radiation exposure, and the ability to acquire perfusion data alongside structural imaging in a single session.

2.2.2.6. Magnetoencephalography (MEG). MEG measures the magnetic fields generated by neuronal activity, offering excellent temporal resolution (milliseconds) and reasonable spatial resolution [42]. It is particularly sensitive to interictal epileptiform discharges, especially those originating from neocortical sources [43]. MEG's ability to detect and localize epileptiform activity complements EEG findings and, when combined with structural imaging (magnetic source imaging), enhances the delineation of epileptogenic zones.

2.2.2.7. HD-EEG. Another promising electrophysiological technique is high-density EEG (HD-EEG), which provides improved spatial resolution over conventional EEG by using a greater number of electrodes (typically 64 to 256 channels)[44]. This allows for a more detailed and localized mapping of brain activity, detecting signals that conventional EEG might miss. HD-EEG improves the detection of interictal epileptiform discharges (IEDs) and seizure onset zones (SOZ)[45]. Studies show that HD-EEG combined with electrical source imaging (ESI) leads to management changes in a higher number of patients compared to conventional EEG, aiding in presurgical evaluation for refractory epilepsy [46]. HD-EEG is effective in identifying biomarkers for diagnosis and prognosis in diseases such as dementia, Parkinson's disease, multiple sclerosis, and stroke. It helps differentiate between disease subtypes, track cognitive decline, and map cortical activity distribution, contributing to more accurate diagnosis and therapeutic monitoring[47]. HD-EEG is significantly less expensive than MEG and more accessible in resource-limited settings, although it requires specialized operator expertise and advanced analytic tools for source localization. Its utility in localizing epileptogenic zones, especially in MRI-negative epilepsy, is gaining recognition and warrants broader integration into clinical protocols[48].

2.2.3. Diagnostic accuracy of functional and metabolic neuroimaging

Positron emission tomography (PET) provides metabolic information by detecting focal hypometabolism with high sensitivity (70–85 %), especially valuable when MRI is negative. PET's high cost, requirement for radiotracers, and limited availability restrict its use to specialized centers [49]. Single photon emission computed tomography (SPECT), particularly ictal SPECT, offers excellent sensitivity (up to 90 %) for localizing seizure onset zones when performed during seizures[50]. Magnetoencephalography (MEG) records magnetic fields generated by neuronal activity with millisecond temporal resolution and high sensitivity (80–90 %) for detecting epileptiform activity, especially from neocortical sources [51]. Functional MRI (fMRI) is particularly valuable in presurgical planning, showing 70–90 % concordance with invasive methods for language lateralization and helping predict postoperative cognitive outcomes [52]. Table 2 provides a summary of structural imaging techniques, key features, diagnostic value and practical considerations

3. Clinical decision framework

3.1. Scenario A- new onset seizures

The clinical application of neuroimaging in epilepsy must be aligned with the patient's presentation, seizure type, and clinical urgency. As described in Fig. 1, for patients presenting with new-onset seizures, the initial imaging modality is often dictated by the clinical context. In emergency or acute care settings, non-contrast computed tomography (CT) remains the first-line imaging tool due to its rapid acquisition time and widespread availability. CT is particularly valuable for excluding life-threatening causes such as hemorrhage, space-occupying lesions, or cerebral edema [53]. However, in non-emergent scenarios or once the patient is stabilized, a high-resolution 3T magnetic resonance imaging (MRI) scan with epilepsy-specific protocols is essential. This includes volumetric T1-weighted sequences, fluid-attenuated inversion recovery (FLAIR), diffusion-weighted imaging (DWI), and coronal oblique views of the hippocampi in line with the HARNESS-MRI protocol recommended by the International League Against Epilepsy (ILAE) Neuroimaging Task Force [15]. Detection of epileptogenic abnormalities such as mesial temporal sclerosis, focal cortical dysplasia, or vascular malformations on MRI allows for tailored medical or surgical interventions. Advanced imaging modalities such as PET, SPECT, and MR spectroscopy (MRS) are typically reserved for patients undergoing pre-surgical evaluation for epilepsy, particularly when MRI findings are inconclusive or when further functional or metabolic information is needed to localize the epileptogenic zone [54]. In cases where MRI is normal and the seizure is isolated, routine clinical follow-up may be appropriate, particularly if the patient is not at high risk for recurrence.

3.2. Scenario B-MRI-Negative epilepsy

In MRI-negative epilepsy, further investigation with functional neuroimaging is often warranted to uncover subtle epileptogenic abnormalities. Fluorodeoxyglucose positron emission tomography (FDG-PET) is the modality of choice for evaluating regional hypometabolism, especially in patients with suspected temporal lobe epilepsy[55]. FDG-PET can detect areas of reduced glucose metabolism that may correlate with seizure onset zones even when structural imaging is inconclusive. Alternatively, ictal single-photon emission computed tomography (SPECT) can provide high spatial resolution of cerebral perfusion changes during seizure onset, making it especially useful in cases of extratemporal epilepsy [56].When both FDG-PET and SPECT fail to identify a definitive seizure focus, additional imaging techniques such as functional MRI (fMRI) for language and memory lateralization, diffusion tensor imaging (DTI) for white matter tract mapping, and magnetic resonance spectroscopy (MRS) for biochemical analysis may be employed. These advanced strategies can collectively offer insight into network dysfunction, aid in lateralization and localization, and determine surgical eligibility.

3.3. Scenario C- drug-resistant epilepsy (presurgical evaluation)

As indicated in Fig. 1, for patients with drug-resistant epilepsy undergoing presurgical evaluation, a comprehensive and multimodal imaging strategy is essential to maximize surgical success and minimize morbidity. The cornerstone of presurgical imaging is a 3T MRI with

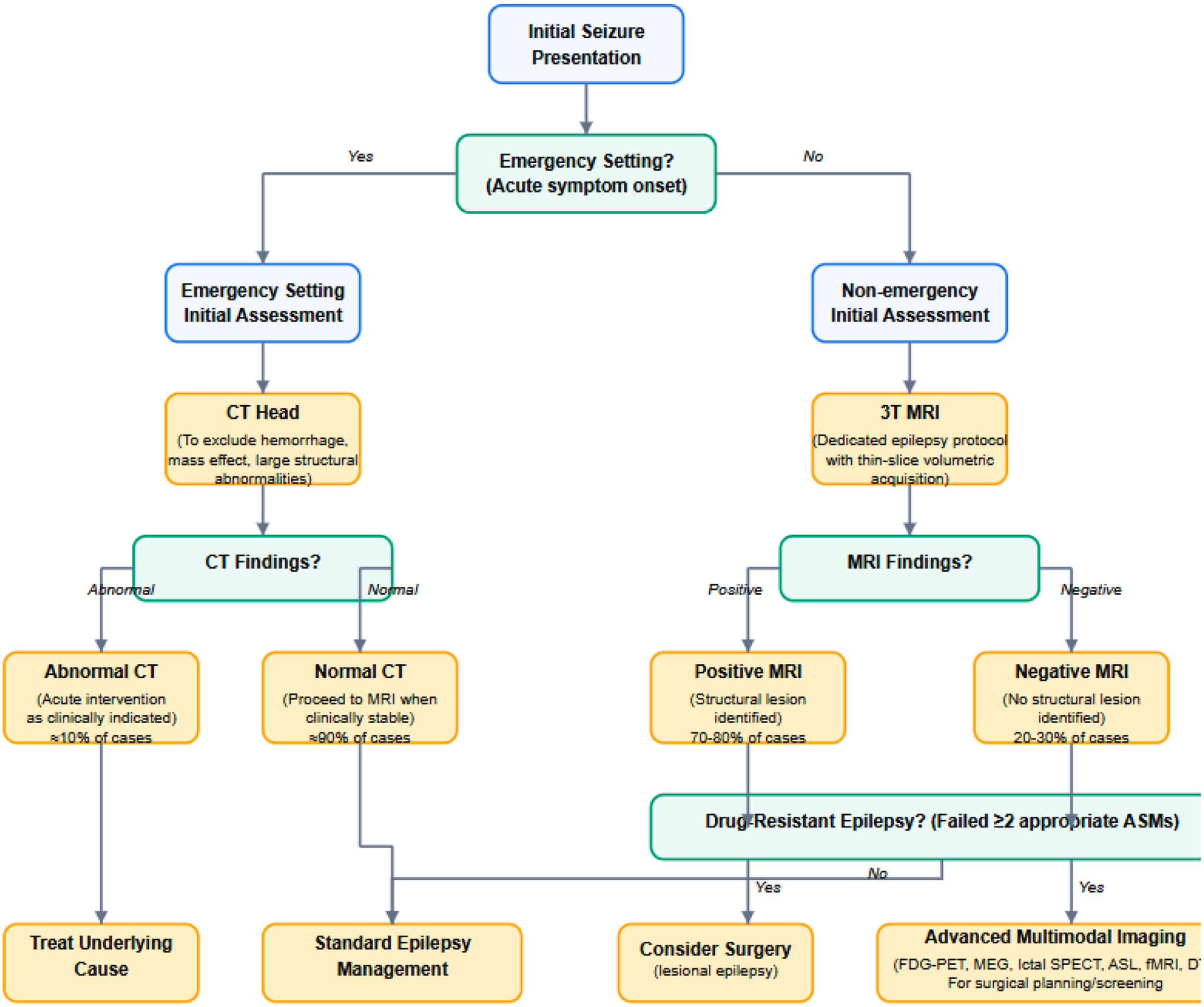

Fig. 1. Neuroimaging Algorithm for Epilepsy.

epilepsy-specific protocol, which must be complemented by fMRI and DTI for functional and structural mapping [57]. This combination allows clinicians to delineate eloquent cortex, visualize white matter pathways, and identify subtle malformations. If MRI findings are non-conclusive or further confirmation is needed, FDG-PET and ictal SPECT can be used to correlate metabolic or perfusion abnormalities with the presumed seizure onset zone. In highly complex or non-lesional epilepsy cases, magnetoencephalography (MEG) offers high temporal and spatial resolution to detect neocortical epileptiform discharge [58]. Moreover, simultaneous EEG-fMRI may be employed in advanced centers to link epileptiform discharges with hemodynamic changes, enhancing the localization of epileptogenic networks. These functional and electrophysiological insights are particularly valuable in patients with discordant or ambiguous findings from structural imaging. Finally, integration of all imaging data using coregistration software facilitates surgical planning and improves outcomes by providing a comprehensive map of the epileptogenic and functionally critical brain regions [54].

4. Challenges and strategies for implementation in low and middle-income countries (LMICS)

While there are many challenges, this review discusses the main challenges which is infrastructure and access challenges, economic and cost barriers and shortage of trained personnel and expertise

4.1. *Challenges*

4.1.1. *Infrastructure and access challenges in structural imaging (MRI/CT)*

In many LMICs, basic structural imaging modalities such as MRI and CT are scarce and unevenly distributed. Sub-Saharan Africa has fewer than one MRI scanner per million persons, according to a needs assessment survey done by Consortium for Advancement of MRI Education and Research in Africa (CAMERA)[59]. MRI is completely unavailable in some nations, such as Mali and the Democratic Republic of the Congo [60]. By contrast, high-income countries often have 10–30+ MRI units per million populations. There are other obstacles to availability, including as finding and keeping qualified workers to run the scanners and having access to steady electricity. Many African and South Asian regions, for example, struggle with power outages and lack on-site engineering expertise for MRI maintenance [60]. It is common for LMIC clinics to rely on older or low-field scanners (e.g. 0.5–1.0T MRI or legacy CT units), which, while providing some diagnostic value, miss the finer detail needed for subtle epilepsy lesions [61]. In resource-limited settings where MRI is out of reach, CT often becomes the default imaging modality despite its lower sensitivity for chronic epileptogenic lesions [61]. However, the heavy reliance on CT (which detects only ~30–40 % of epileptogenic lesions means many patients with surgically remediable epilepsy (e.g. focal cortical dysplasias or hippocampal sclerosis) remain undiagnosed.

Geographical misdistribution further complicates access: most imaging facilities in LMICs are concentrated in major cities, leaving rural populations with virtually no local access[60]. Patients often must travel long distances or pay out-of-pocket for private imaging. Given that health insurance coverage is limited, many families incur catastrophic expenses or forgo imaging entirely. As the WHO notes, up to 75 % of epilepsy patients in low-income countries do not get the care they need [1]. Lack of diagnostic imaging is a key contributor to this care gap.

4.1.2. *Economic and cost barriers*

Purchasing a modern MRI or PET scanner can run into the hundreds of thousands to millions of USD, a prohibitive expense for many public hospitals. But the initial price tag is just the “tip of the iceberg” when it comes to cost [62]. The ongoing operational and maintenance costs – including electricity (or liquid helium for MRI magnets), service contracts, replacement parts, and software upgrades – are substantial and often not budgeted for in LMIC settings [60]. One analysis from India found that running a PET/CT center incurred about $1 million per year in costs, with only 24 % attributable to operating the machine and the rest due to capital depreciation and staffing [62]. For an underfunded public hospital, such recurrent expenditures are unsustainable without external support or high patient fees. Additionally, advanced modalities come with *indirect* costs: PET and SPECT require radiopharmaceuticals (necessitating either a local cyclotron or import logistics), and MEG requires costly liquid helium and shielded rooms for operation. These factors explain why 95 % of low-income countries and over 90 % of lower-middle income countries have no PET/CT units at all [62]. Even MRI, which has no consumable isotopes, may be priced out of reach for patients when healthcare is mostly out-of-pocket – families in LMICs sometimes must borrow large sums for an MRI scan[60].

4.1.3. *Shortage of trained personnel and expertise*

A less visible but critical challenge in LMICs is the limited availability of trained professionals to perform and interpret neuroimaging for epilepsy. Radiologists, neuroradiologists, nuclear medicine physicians, technicians, and biomedical engineers are in short supply in many low-resource countries[62]. This skills gap leads to suboptimal utilization of the technology that is available – e.g. an MRI scanner might be underused or misused if technologists cannot run advanced epilepsy sequences, or radiologists miss abnormalities that a trained eye would catch. The brain drain phenomenon exacerbates this: LMIC institutions struggle to retain skilled imaging experts, who often migrate to higher-income settings for better pay and working conditions[60]. As a result, even when modern scanners are installed, they may sit idle or produce low-yield results due to lack of local expertise. In the realm of advanced imaging, the personnel gap is even wider: performing an ictal SPECT study or interpreting a PET scan for epilepsy requires a multidisciplinary team (epileptologist, technologist, radiochemist, etc.) that is rarely fully present in LMIC settings.

4.2. *Strategies for implementation*

4.2.1. *Infrastructure and access challenges*

Improving structural imaging infrastructure in LMICs requires coordinated investment and innovative approaches. A fundamental step is for governments and partners to prioritize MRI acquisition as part of epilepsy care infrastructure. Recognizing this, some countries have launched public-private partnerships to finance scanners. For example, Kenya’s federal government partnered with an equipment vendor (General Electric) to fund dozens of MRI machines nationwide, dramatically improving access in recent years [60]. Nigeria has similarly increased its health technology investments, acquiring new MRI units through government funding initiatives [60]. These efforts illustrate that creative financing and political will can overcome the initial infrastructure barrier.

International support and advocacy can also play a role. The Consortium for Advancement of MRI Education and Research in Africa (CAMERA) and other advocacy groups have highlighted technological innovations such as low-field or portable MRI systems that are cheaper, do not require cryogens, and can operate on lower power, making them suitable for resource-limited hospitals [59]. Such low-cost MRI innovations are being piloted to extend imaging to remote or underserved areas. In the interim, when MRI is unavailable, standardized epilepsy-protocol CT scans can be used to identify obvious lesions (tumors, cysticercosis, gross malformations) so that at least some treatable causes of seizures are recognized [61]. Ultimately, a tiered imaging network is advised: primary centers should have access to CT for acute cases, while regional or national centers are equipped with at least a 1.5T or 3T MRI dedicated to epilepsy evaluation. Ensuring reliable power supply (via generators or voltage regulators) and training local biomedical engineers for maintenance are crucial accompanying measures. Notably, the cost of maintenance is often as important as purchase – spare parts and service contracts should be planned upfront to avoid idle machines[59]. Some LMIC hospitals have addressed maintenance gaps by entering service agreements with companies or engaging diaspora engineers, though long-term the goal is to build in-country technical capacity.

4.2.2. *Economic and cost barriers*

Tackling cost barriers calls for both top-down and bottom-up solutions. At the national level, governments can integrate neuroimaging into health budgets and seek international funding or development loans specifically for diagnostic imaging expansion. Cost-effectiveness studies have shown that appropriately used imaging (e.g. MRI for surgical candidate evaluation) can be highly cost-effective by guiding curative epilepsy surgeries, which in turn reduce long-term healthcare and social costs [62]. Communicating such data to policymakers helps justify upfront investments. Another approach is leveraging philanthropic donations and global health initiatives: organizations such as the WHO and International Atomic Energy Agency (IAEA) have programs to donate or subsidize imaging equipment in LMICs and train staff to use them.

For instance, the IAEA has supported nuclear medicine departments in some African and Asian countries, supplying SPECT cameras and training, thereby indirectly benefiting epilepsy care where those cameras can be used for ictal SPECT studies. Local production or regional sharing of resources can also defray costs – e.g. a regional cyclotron center serving multiple hospitals/countries to provide PET tracers more affordably, or rotating a mobile MRI unit through multiple smaller hospitals. On the patient side, expanding insurance coverage or government-subsidized imaging vouchers can protect impoverished families from catastrophic health expenditures. Countries such as Brazil and Thailand, for example, have national health schemes that cover basic imaging, dramatically increasing utilization by removing cost barriers at the point of care [62]. Finally, prioritization is key: experts recommend that resource-limited health systems invest first in a high-quality MRI service with an epilepsy-focused protocol before pursuing more advanced (and expensive) technologies. This phased approach ensures that limited funds yield the greatest clinical impact.

4.2.3. *Shortage of trained personnel and expertise*

Capacity building through education and training is the cornerstone of addressing the human resource gap. International collaborations have shown success in knowledge transfer. For instance, in the Epilepsy Surgery Initiative in Vietnam and Cambodia, visiting neurologists and radiologists from established epilepsy centers helped train local teams in reading MRI and planning surgery, enabling those countries to start their own programs. A broader recommendation is to establish “twinning” or mentoring programs: an LMIC epilepsy center partners with a well-established center in a high-income country to receive ongoing training, case consultations, and mentorship [61]. This approach was emphasized in a 2022 outline for initiating epilepsy surgery in LMICs, which noted that lack of local expertise is the major obstacle, and that it “can be compensated by collaborating with a well-established epilepsy center for knowledge transfer, skill building and mentoring"[61]. Within radiology, initiatives such as the RAD-AID program and teleradiology services have been used to bridge expertise gaps: difficult neuroimaging cases from an LMIC can be reviewed remotely by subspecialists abroad, improving diagnostic yield

5. Conclusions

Neuroimaging plays an indispensable role in the diagnosis and management of epilepsy. This review highlights the strengths and limitations of both structural and functional modalities, demonstrating their complementary value in different clinical scenarios from new-onset seizures to MRI-negative and drug-resistant epilepsy cases. The proposed clinical decision-making framework serves as a practical guide for tailoring imaging strategies based on urgency, clinical setting, and available resources. Moreover, addressing implementation challenges in LMICs remains critical. Solutions such as tiered imaging infrastructure, cost-sharing models, training partnerships, and the adoption of low-field or portable imaging technologies can significantly bridge the diagnostic gap. Ultimately, the successful integration of multimodal neuroimaging guided by clinical context and supported by strategic health investment can transform epilepsy care and outcomes, particularly in resource-constrained settings.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

This is a review article and does not involve the collection or analysis of primary data. All data supporting the findings of this study are derived from previously published sources, which are appropriately cited within the manuscript.

CRediT authorship contribution statement

Bright Worlanyo Aklamanu: Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their sincere gratitude to the clinical and administrative staff at FOCOS Orthopaedic Hospital for their invaluable support throughout the course of this work. Their dedication, expertise, and collaborative spirit significantly contributed to the development and refinement of this review.

References

[1] World Health Organisation (WHO), "Epilepsy." Accessed: Apr. 10, 2025. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/epilepsy.
[2] J.S. Duncan, G.P. Winston, M.J. Koepp, S. Ourselin, Brain imaging in the assessment for epilepsy surgery, Lancet Neurol 15 (4) (2016) 420–433.
[3] R.E. Feldman, et al., Quantification of perivascular spaces at 7 T: a potential MRI biomarker for epilepsy, Seizure 54 (2018) 11–18.
[4] K.A. Alsharif, M.S. Alenazi, The role of CT scan in comprehensive and early diagnosis of strokes and severe head injuries, Multi-Knowledge Electron. Compr. J. Educ. Sci. Publ. (68) (2023).
[5] M.A. Nieto-Salazar, et al., Diagnostic implications of neuroimaging in epilepsy and other seizure disorders, Ann. Med. Surg. 85 (2) (2023) 73–75.
[6] P. Desale, et al., Navigating neural landscapes: a comprehensive review of magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) applications in epilepsy, Cureus 16 (3) (2024).
[7] A.H. Krish, Comparative analysis of traditional and modern imaging techniques in neurological disorders, Int. J. Multidiscip. Res. 6 (5) (2024), https://doi.org/10.36948/ijfmr.2024.v06i05.27223.
[8] S. Chinchure, C. Kesavadas, B. Thomas, Structural and functional neuroimaging in intractable epilepsy, Neurol. India 58 (3) (2010) 361–370.
[9] W. Mier, D. Mier, Advantages in functional imaging of the brain, Front. Hum. Neurosci. 9 (2015) 249.
[10] A. De Vito, K. Mankad, S. Pujar, A. Chari, D. Ippolito, F. D'Arco, Narrative review of epilepsy: getting the most out of your neuroimaging, Transl. Pediatr. 10 (4) (2021) 1078.
[11] S.D. Serai, Basics of magnetic resonance imaging and quantitative parameters T1, T2, T2*, T1rho and diffusion-weighted imaging, Pediatr. Radiol. 52 (2) (2022) 217–227.
[12] P. Widdess-Walsh, B. Diehl, I. Najm, Neuroimaging of focal cortical dysplasia, J. Neuroimaging 16 (3) (2006) 185–196.
[13] C.H. Sotak, The role of diffusion tensor imaging in the evaluation of ischemic brain injury–a review, NMR Biomed. An Int. J. Devoted to Dev. Appl. Magn. Reson. Vivo 15 (7–8) (2002) 561–569.
[14] S.F. Elkholy, M.A. Sabet, M.E. Mohammad, R.E.I. Asaad, Comparative study between double inversion recovery (DIR) and fluid-attenuated inversion recovery (FLAIR) MRI sequences for detection of cerebral lesions in multiple sclerosis, Egypt. J. Radiol. Nucl. Med. 51 (2020) 1–10.
[15] A. Bernasconi, et al., Recommendations for the use of structural magnetic resonance imaging in the care of patients with epilepsy: a consensus report from the International League Against Epilepsy Neuroimaging Task Force, Epilepsia 60 (6) (2019) 1054–1068.
[16] K. Kotisaari, P. Virtanen, N. Forss, D. Strbian, F. Scheperjans, Emergency computed tomography in patients with first seizure, Seizure 48 (2017) 89–93.
[17] N. Farid, et al., Temporal lobe epilepsy: quantitative MR volumetry in detection of hippocampal atrophy, Radiology 264 (2) (2012) 542–550.
[18] Y. Assaf, O. Pasternak, Diffusion tensor imaging (DTI)-based white matter mapping in brain research: a review, J. Mol. Neurosci. 34 (2008) 51–61.
[19] T. Hammen, R. Kuzniecky, Magnetic resonance spectroscopy in epilepsy, Handb. Clin. Neurol. 107 (2012) 399–408.
[20] T. Thesen, et al., Detection of epileptogenic cortical malformations with surface-based MRI morphometry, PLoS One 6 (2) (2011) e16430.
[21] B. Adamczyk, K. Węgrzyn, T. Wilczyński, J. Maciarz, N. Morawiec, M. Adamczyk-Sowa, The most common lesions detected by neuroimaging as causes of epilepsy, Medicina (B. Aires). 57 (3) (2021) 294.
[22] E. Tranvinh, B. Lanzman, J. Provenzale, M. Wintermark, Imaging evaluation of the adult presenting with new-onset seizure, Am. J. Roentgenol. 212 (1) (2019) 15–25.
[23] C.A. Cuenod, L. Fournier, D. Balvay, J.-M. Guinebretiere, Tumor angiogenesis: pathophysiology and implications for contrast-enhanced MRI and CT assessment, Abdom. Imaging 31 (2006) 188–193.
[24] A. Zafar, et al., Cerebral vascular malformations and their imaging modalities, Neurol. Sci. 41 (2020) 2407–2421.
[25] P.J. Magistretti, I. Allaman, A cellular perspective on brain energy metabolism and functional imaging, Neuron 86 (4) (2015) 883–901.
[26] M. Boly, O. Gosseries, M. Massimini, M. Rosanova, Functional neuroimaging techniques. The Neurology of Conciousness, Elsevier, 2016, pp. 31–47.
[27] L. Zimmer, A. Luxen, PET radiotracers for molecular imaging in the brain: past, present and future, Neuroimage 61 (2) (2012) 363–370.
[28] M. Hodolic, R. Topakian, R. Pichler, 18F-fluorodeoxyglucose and 18F-flumazenil positron emission tomography in patients with refractory epilepsy, Radiol. Oncol. 50 (3) (2016) 247.
[29] I. Sarikaya, PET studies in epilepsy, Am. J. Nucl. Med. Mol. Imaging 5 (5) (2015) 416.
[30] D. Linden, Neuroimaging and Neurophysiology in Psychiatry, Oxford University Press, 2016.
[31] G. Crişan, N.S. Moldovean-Cioroianu, D.-G. Timaru, G. Andrieş, C. Căinap, V. Chiş, Radiopharmaceuticals for PET and SPECT imaging: a literature review over the last decade, Int. J. Mol. Sci. 23 (9) (2022) 5023.
[32] C. La Fougère, A. Rominger, S. Förster, J. Geisler, P. Bartenstein, PET and SPECT in epilepsy: a critical review, Epilepsy Behav 15 (1) (2009) 50–55.
[33] H.W. Lee, S.B. Hong, W.S. Tae, Opposite ictal perfusion patterns of subtracted SPECT: hyperperfusion and hypoperfusion, Brain 123 (10) (2000) 2150–2159.
[34] W. Ghebretensay, Subtraction Ictal SPECT Co-Registered to MRI (SISCOM), Society of Nuclear Medicine, 2011.
[35] P.A. Bandettini, fMRI: blood oxygen level-dependent contrast and its value for understanding functional brain networks. Brain Network Dysfunction in Neuropsychiatric Illness: Methods, Applications, and Implications, Springer, 2021, pp. 19–44.
[36] C. Fu, A. Aisikaer, Z. Chen, Q. Yu, J. Yin, W. Yang, Different functional network connectivity patterns in epilepsy: a rest-state fMRI study on mesial temporal lobe epilepsy and benign epilepsy with centrotemporal spike, Front. Neurol. 12 (2021) 668856.
[37] U.J. Chaudhary, Haemodynamic Correlates of Interictal and Ictal Epileptic Discharges and Ictal Semiology Using Simultaneous Scalp video-EEG-fMRI and Intracranial EEG-fMRI, UCL (University College London, 2013.
[38] V. Singh, Advancements and applications of MR spectroscopy in neuroimaging: a comprehensive review, Int. J. Med. Sci. Clin. Res. Rev. 7 (4) (2024) 730–750.
[39] M. Navidhamidi, M. Ghasemi, N. Mehranfard, Epilepsy-associated alterations in hippocampal excitability, Rev. Neurosci. 28 (3) (2017) 307–334.

[40] M. Taso, et al., Update on state-of-the-art for arterial spin labeling (ASL) human perfusion imaging outside of the brain, Magn. Reson. Med. 89 (5) (2023) 1754–1776.

[41] M. Schertz, et al., Specificities of arterial spin labeling (ASL) abnormalities in acute seizure, J. Neuroradiol. 47 (1) (2020) 20–26.

[42] M. Hämäläinen, R. Hari, Magnetoencephalographic (MEG) characterization of dynamic brain activation, Brain Mapp. methods, Ed 2 (2002) 227–254.

[43] C. Laohathai, et al., Practical fundamentals of clinical MEG interpretation in epilepsy, Front. Neurol. 12 (2021) 722986.

[44] S.M. Stoyell, et al., High-density EEG in current clinical practice and opportunities for the future, J. Clin. Neurophysiol. 38 (2) (2021) 112–123.

[45] Y. Li, et al., Impact of high-density EEG in presurgical evaluation for refractory epilepsy patients, Clin. Neurol. Neurosurg. 219 (2022) 107336.

[46] M. Heers, et al., Detection of interictal epileptiform discharges in an extended scalp EEG array and high-density EEG—A prospective multicenter study, Epilepsia 63 (7) (2022) 1619–1629.

[47] C. Formica, et al., The role of high-density EEG in diagnosis and prognosis of neurological diseases: a systematic review, Clin. Neurophysiol. (2025).

[48] L. Yao, et al., Advances in neuroimaging and multiple post-processing techniques for epileptogenic zone detection of drug-resistant epilepsy, J. Magn. Reson. Imaging 60 (6) (2024) 2309–2331.

[49] J.G. Burneo, R. Poon, S. Kellett, O.C. Snead 3rd, The utility of positron emission tomography in epilepsy, Can. J. Neurol. Sci. 42 (6) (2015) 360–371.

[50] R.C. Knowlton, The role of FDG-PET, ictal SPECT, and MEG in the epilepsy surgery evaluation, Epilepsy Behav 8 (1) (2006) 91–101.

[51] D.J. Englot, et al., Epileptogenic zone localization using magnetoencephalography predicts seizure freedom in epilepsy surgery, Epilepsia 56 (6) (2015) 949–958.

[52] J.P. Szaflarski, et al., Practice guideline summary: use of fMRI in the presurgical evaluation of patients with epilepsy: report of the Guideline Development, Dissemination, and Implementation Subcommittee of the American Academy of Neurology, Neurology 88 (4) (2017) 395–402.

[53] S. Lietke, S. Zausinger, M. Patzig, M. Holtmanspötter, M. Kunz, CT-based classification of acute cerebral edema: association with intracranial pressure and outcome, J. Neuroimaging 30 (5) (2020) 640–647.

[54] K. Yoganathan, N. Malek, E. Torzillo, M. Paranathala, J. Greene, Neurological update: structural and functional imaging in epilepsy surgery, J. Neurol. 270 (5) (2023) 2798–2808.

[55] Y. Tang, et al., [18F] FDG PET metabolic patterns in mesial temporal lobe epilepsy with different pathological types, Eur. Radiol. 34 (2) (2024) 887–898.

[56] S. Jayalakshmi, P. Sudhakar, M. Panigrahi, Role of single photon emission computed tomography in epilepsy, Int. J. Mol. Imaging 2011 (1) (2011) 803920.

[57] A. Berger, et al., Preoperative localization of seizure onset zones by magnetic source imaging, EEG-correlated functional MRI, and their combination, J. Neurosurg. 134 (4) (2020) 1037–1043.

[58] M. Javidan, Electroencephalography in mesial temporal lobe epilepsy: a review, Epilepsy Res. Treat. 2012 (1) (2012) 637430.

[59] U.C. Anazodo, et al., A framework for advancing sustainable magnetic resonance imaging access in Africa, NMR Biomed 36 (3) (2023) e4846.

[60] U. Kwikima, Looking towards the future of MRI in Africa, Nat. Commun 15 (1) (2024) 1–4, https://doi.org/10.1038/s41467-024-46567-3.

[61] P. Bäuerle, U. Schneider, M. Holtkamp, T. Gloveli, T. Dugladze, Outlines to initiate epilepsy surgery in low- and middle-income countries, J. Integr. Neurosci. 21 (5) (2022), https://doi.org/10.31083/j.jin2105134.

[62] H.C. Verduzco-Aguirre, G. Lopes, E. Soto-Perez-De-Celis, Implementation of diagnostic resources for cancer in developing countries: a focus on PET/CT, Ecancermedicalscience (13) (2019) 2–6, https://doi.org/10.3332/ECANCER.2019.ED87.