Treatment-resistant Lennox-Gastaut syndrome: therapeutic trends, challenges and future directions

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Abstract: Lennox-Gastaut syndrome is a severe, childhood-onset electroclinical syndrome comprised of multiple seizure types, intellectual and behavioral disturbances and characteristic findings on electroencephalogram of slow spike and wave complexes and paroxysmal fast frequency activity. Profound morbidity often accompanies a common and severe seizure type, the drop attack. Seizures often remain refractory, or initial treatment efficacy fades. Few individuals are seizure free despite the development of multiple generations of antiseizure medications over decades and high-level evidence on several choices. Approved medications such as lamotrigine, topiramate, rufinamide, felbamate and clobazam have demonstrated efficacy in reducing seizure burden. Cannabidiol has emerged as a promising investigational therapy with vast social interest yet lacks a standard, approved formulation. Palliative surgical procedures, such as vagal nerve stimulation and corpus callosotomy may provide reduction in total seizures and drop attacks. Emerging evidence suggests that complete callosotomy provides greater improvement in seizures without additional side effects. Etiologies such as dysplasia or hypothalamic hamartoma may be amenable for focal resection and thus offer potential to reverse this devastating epileptic encephalopathy.

Keywords: Lennox-Gastaut syndrome, epilepsy, epilepsy surgery, cannabidiol, epileptic encephalopathy

Introduction

Five decades ago, Gastaut et al1 summarized a clinical syndrome manifested as a “childhood epileptic encephalopathy with diffuse slow spikes-and-waves”. Later termed as Lennox-Gastaut syndrome (LGS), this devastating epileptic encephalopathy remains one of the most treatment-resistant epilepsies across the age spectrum. LGS is currently classified by the International League Against Epilepsy (ILAE) as a childhood-onset electroclinical syndrome and epileptic encephalopathy comprised by the triad of, 1) polymorphic intracranial seizures that are mainly tonic, atonic and atypical absence seizures; 2) cognitive and behavioral abnormalities; and 3) electroencephalogram (EEG) with paroxysms of fast activity and slow (<2.5 Hz) generalized spike wave discharges (Figure 1).2,3

The syndrome occurs in 2.8 per 100,000 live births4 and comprises ~4%–10% of childhood epilepsy.5–7 Onset is typically between 1 and 7 years and is five times more common in boys.8 Prognosis is poor, as less than 10% achieve seizure freedom as adults.9 Most individuals with LGS develop comorbid autism, intellectual disability and other behavioral concerns.9 Attention to these significant comorbidities is crucial in improving the quality of life in individuals with LGS; yet, no treatment specific to patients with LGS exists for these concerns. Patients’ families have reported that their most significant concerns are fear of dying and the unpredictability of seizures, side effects and social isolation.10,11 These data may suggest prioritizing seizure control and facilitating interactions with appropriate support networks.
Features portending a poor prognosis include pre-existing West syndrome, early age of onset, symptomatic causes, abnormal neuroimaging, more frequent seizures or status epilepticus or focal/multifocal EEG abnormalities. Importantly, individuals with LGS have many risk factors for sudden unexplained death in epilepsy (SUDEP), such as frequent generalized tonic clonic seizures, early age of epilepsy, long duration of epilepsy and intellectual disability. Early death occurs in up to 15% of individuals with LGS.

An extremely heterogeneous set of causes lead to a common syndrome in individuals with LGS. Structural etiologies, including hypoxic–ischemic encephalopathy, meningoencephalitis, neurocutaneous disorders and brain malformations, including hypothalamic hamartomas and metabolic syndromes, account for ~70%–80% of all cases. Presumed genetic or unknown causes represent the other 20%–30%. De novo mutations in ALG13 and GABRB3 have been described as causative in individuals with LGS. Other genes implicated include CHD2, DNM1, CACNA1A, CHD2, FLNA, GABRA1, GRIN1, GRIN2A, GRIN2B, HDAC3, HNRNPU, IQSEC2, mTOR, NEDD4L and SCN8A, STXBP1 and SYNGAP1. Infantile spasms precede the development of LGS in up to 60% of children, more often if West syndrome was symptomatic.

Medical therapies – general principles and challenges

Despite decades of medical advances, controlling seizures in patients with LGS remains a challenge for the clinician. More than 90% of children with LGS have drug-resistant epilepsy. Balancing seizure control and side effects using rational polypharmacy is challenging. While some combinations of antiseizure medications demonstrate therapeutic synergies, additive side effects can occasionally worsen seizures and often cause behavioral problems and increased sedation. Direct comparative drug trials in patients with LGS have not been performed. Six antiseizure medications hold US Food and Drug Administration (FDA) indications for the treatment of LGS, which include lamotrigine, topiramate, felbamate, rufinamide, clobazam and clonazepam. Notwithstanding multiple treatment options, long-term seizure control remains elusive.

Comparing treatment efficacy in patients with LGS is challenging due to several factors. The reduction in seizures in individuals with LGS tends to diminish over time. Long-term follow-up for more than 12 months in prospective studies is often expensive and logistically challenging. The heterogeneity of seizure types in studies can be confounding, particularly the often-reported drop seizures. Most drop
Medical therapies – available treatments

Medical management is guided not by comparative drug studies but by physician preference, experience and adjunctive treatment studies with varying levels of evidence. Polytherapy is often required. Based on expert opinion and practice, valproate, topiramate and lamotrigine are considered as first-line therapies. After FDA approval for use in the United States, clobazam has become a commonly used early adjunctive treatment for LGS. More than 100 nonrandomized controlled trials (level III) and case–control or cohort series (level IV) addressing the treatment of LGS have been published. To emphasize higher quality evidence for pharmacotherapy, we present efficacy data solely from level I or level II studies. In addition, we briefly address several other medications without mentioning efficacy data in an attempt to help readers navigate the spectrum of commonly used therapies.

We also describe existing evidence for dietary therapy and epilepsy surgical techniques. Although lower level data may provide important insights, we recommend providers focus on higher quality evidence for the initial management of LGS. We have also shared our experience and expert opinions.

First-generation antiseizure medications remain popular early therapies for the treatment of LGS. Despite its age and lack of level I or level II evidence, valproate remains a mainstay in treatment and is often the first-line medication for LGS. Valproate carries risk of hepatotoxicity and thrombocytopenia, which may worsen with polytherapy (see later in this section). Other first-generation antiseizure medications are less commonly used. Carbamazepine may be helpful for focal or tonic seizures in individuals with LGS related to a focal structural lesion. However, it may exacerbate absence seizures and myoclonic seizures.

Ethosuximide may be effective in controlling atypical absence seizures, negative myoclonus and tonic seizures, but would not be expected to treat generalized tonic or tonic-clonic seizures. Clonazepam may be effective for myoclonic or tonic seizures but is associated with more common side effects compared to clobazam and has more tachyphylaxis.
be better seizure control and less sedation, there is increased (resumption of) spasticity in patients with cerebral palsy. Phenobarbital may decrease the convulsive seizures but exacerbate absences.\(^5\)

Lamotrigine, topiramate, felbamate and levetiracetam are second-generation antiseizure medications commonly prescribed for patients with LGS and typically with better tolerability. Levetiracetam demonstrated efficacy in small cohorts of patients with LGS and remains a common choice due to an exemplary safety and tolerability profile.\(^31,32\)

Adjunctive lamotrigine has been studied in a class I trial of 169 patients with LGS and demonstrated a \(>50\%\) reduction in seizures in 33\% of patients compared to 16\% in the placebo group.\(^33\) Overall, seizure reduction was significant (\(-32\%\) vs \(-9\%\) placebo). This included a statistically significant decrease in drop attacks (tonic, atonic and major myoclonic seizures). A higher percentage of patients in the lamotrigine group compared to the placebo group were on valproate (67\% to 50\%, respectively). Adverse drug events were similar between study drug and placebo groups. Despite this evidence, lamotrigine should be used with caution in patients with a significant number of myoclonic seizures, as it may cause exacerbations of this seizure type.\(^5,34\)

Topiramate was studied in a class I trial in 98 patients with LGS.\(^35\) Results did not demonstrate a statistically significant decrease in total seizures (\(-21\%\) vs \(-9\%\)), although greater than 50\% reduction in major seizures occurred in a larger proportion of patients in the treatment arm (33\% on topiramate vs 8\% placebo). Drop attacks were reduced with topiramate (14\% reduction vs 5\% increase in placebo group). Although adverse events were common, they did not lead to discontinuation of the study drug. The treatment effect dissipated by 30 months.\(^36\)

High-level evidence also exists for felbamate, although it is less commonly used due to concerns regarding side effects. Felbamate likely has multiple mechanisms of action, including as an antagonist at the N-methyl-D-aspartate receptor. Adjunctive treatment with felbamate in a class I study of 73 individuals with LGS significantly reduced all seizure types studied (\(-19\%\) vs \(+4\%\) placebo), although absences were not evaluated and video monitoring did not demonstrate a difference in the frequency of seizures.\(^37,38\) Total responders with \(>50\%\) reduction in seizures included 50\% of patients treated with felbamate and 15\% in the placebo arm. Adverse drug events were similar in frequency between the two groups, and global functioning improved. This effect was sustained for 12 months in an open-label study following trial completion.\(^39\)

Although several other studies have demonstrated felbamate effective in LGS,\(^38,40\) clinicians remain judicious with its use.\(^24,25\) Postmarketing analysis has revealed felbamate may cause aplastic anemia (1 in 5,000–10,000) and hepatic failure (1 in 26,000 to 34,000).\(^31,41\) In comparison, the risk of aplastic anemia with carbamazepine is between 1 in 50,000–200,000 and the risk of hepatic failure with valproate ranges from 1 in 500 (children less than 2 years of age), 1 in 12,000 (polytherapy) and 1 in 37,000 (monotherapy).\(^42\)

Newer third-generation antiseizure medications have demonstrated efficacy and tolerability in patients with LGS. Rufinamide is a third-generation antiseizure medication that likely prolongs inactivation of sodium channels. In a placebo-controlled study of adjunctive treatment in 138 individuals with LGS, the overall median of total seizures was significantly reduced (33\% vs 12\%).\(^43\) Drop seizures, identified as tonic–atonic seizures, were reduced (\(-43\%\) vs \(+1\%\) placebo). Somnolence and vomiting were more common in the treatment group, and 8\% of patients receiving rufinamide withdrew due to side effects. Rufinamide was safe and well tolerated in pediatric subjects. Results from the interim analysis demonstrate that the safety and pharmacokinetic profile of rufinamide in subjects with LGS aged between 1 and 4 years is comparable to that in subjects aged \(\geq 4\) years.\(^44\)

Clobazam is a 1,5-benzodiazepine, which binds type A gamma-aminobutyric acid (GABA\(_A\)) receptors, enhancing the inhibitory effect of GABA on neuron excitability. In a class II study of 238 individuals with LGS treated with 0.25, 0.5 or 1 mg/kg/d of clobazam vs placebo, overall responders with \(>50\%\) seizure reduction were 43\%, 59\% and 78\%, respectively, compared to 32\% for placebo.\(^45\) The median reduction in seizures in the high-dose group was 65\% vs 9\% in the placebo group. Drop seizures were reduced by 68\% in the 1 mg/kg/d clobazam arm compared to 12\% in the placebo group. Common adverse events related to clobazam included somnolence, pyrexia, lethargy, drooling and constipation and severe adverse events occurred in 7\% of patients. This was a class II, as opposed to class I study because only \(-79\%\) of the patients with intention to treat analysis completed the study (\(\geq 80\%\) of patients needed to be a class I study); the largest LGS study to date.

Zonisamide likely has multiple mechanisms of action, including reducing inward T-type Ca\(^2+\) currents, blocking sodium channels and facilitating dopaminergic and serotonergic neurotransmission. An open-label adjunctive
Dietary therapies

Dietary therapies, including the classic ketogenic diet and its variants, have demonstrated efficacy in multiple epileptic syndromes. The mechanisms of action are incompletely understood, but likely decrease neuronal excitability through carbohydrate reduction, potassium channel activation, inhibition of the mammalian target of rapamycin (mTOR) pathway and inhibition of glutamatergic-mediated neuronal excitability. A randomized, blinded cross-over study of 20 children with LGS over a 6-day period did not produce a significant reduction in EEG-identified or parent-reported (median decrease of 1.5 seizures in the ketogenic arm, \( P=0.07 \)) seizures, although some children in the nonketogenic arm had remained in ketosis and likely altered the validity of the comparison. An extension of this study demonstrated a reduction in seizures that persisted at 12 months. A study of the ketogenic diet in 71 children with LGS demonstrated a >50% reduction in total seizures in 51% of patients, including a >90% reduction in seizures in nearly one-quarter of those treated. Although effective, the use of these therapies remains limited due to difficulty restricting the dietary habits of individuals with LGS.

Surgical therapy

Surgical therapy for individuals with treatment-resistant epilepsy remains the most successful approach for long-term seizure control. LGS has historically been described as an incurable epileptic encephalopathy due to the often diffuse or generalized EEG findings and intractable seizures despite aggressive medical management. However, numerous advances in neuroimaging and neurophysiology have enabled better identification and treatment of epileptogenic zones. Resective surgery may benefit those with focal lesions, such as dysplasias, hamartomas or infarcts. A retrospective cohort of 27 children and adolescents with LGS (85% lesional on magnetic resonance imaging [MRI]) undergoing resective epilepsy surgery demonstrated seizure freedom in 60% and improvement in another 15% with a mean follow-up of 33 months. In two other case reports, individuals with LGS secondary to focal cortical dysplasias or heterotopia were seizure free following resective surgery. In 21 patients with LGS secondary to hypothalamic hamartoma, 95% had a greater than 50% reduction in seizures, with 24% seizure free following surgery. Initial results can be encouraging; however, the effect of surgical resection tends to wane similar to other therapies. Focal resective surgery initially resulted in Engel class I outcomes in 10/15 patients, although seizure freedom in adulthood only occurred in 3/15. While carefully selected patients with LGS will be candidates for resective surgery aimed at curing their epilepsy, many others may benefit from a surgical approach. Palliative surgical approaches are commonly used to optimize seizure control in individuals with LGS, especially those with the significant morbidity of drop attacks. The vagus nerve stimulator (VNS) implantation is a minimally invasive, reversible procedure without the risk of craniotomy with well-established efficacy in treating epilepsy despite an unknown mechanism of action. Corpus callosotomy (CC) involves severing the main interhemispheric white matter tract through a craniotomy, making this a more invasive surgical option.

A meta-analysis of CC compared to VNS included analysis of 203 VNS patients and 135 CC patients. The authors found that a larger number of patients with CC had a >50% reduction in tonic–clonic, astatic, absence, myoclonic and focal onset seizures with dyscognitive features when compared with anterior 2/3 callosotomy. Between...
61% and 85% of patients achieve an 80% or greater reduction in drop seizures, including 48% of individuals free of drop seizures following the procedure. These data indicate that complete CC may provide superior seizure control over anterior 2/3 CC (Figure 5).

The safety and tolerability of VNS is favorable, with side effects including hoarseness, coughing, tingling in the throat and voice changes occurring in less than 4% of individuals. Complications from CC are more common, occurring in ~8% of patients and include perioperative complications such as infarct or meningitis or transient neurological deficits such as akinesia, mutism, hemiparesis, disconnection syndrome and constructional apraxia. As with all surgical procedures, complications may vary between centers.

**Synergy**

Several treatment options have been studied in combination and may provide synergies. A retrospective analysis of 30 children treated with both VNS and dietary therapy demonstrated a >50% reduction in seizures in 70% of patients. Distinct surgical approaches have been combined in individuals with LGS. In a study including 23 children receiving simultaneous resective surgery and CC demonstrated a greater improvement in quality of life and intelligence quotient. Seizure outcomes were not statistically different compared to medical or resection-only procedures. In other instances, CC may lead to lateralization or localization of diffuse EEG ictal and/or interictal findings. The combination of the palliative procedures VNS and CC in 10 individuals with LGS provided a greater than 50% reduction in seizures in 60% of patients and 2/10 demonstrating seizure freedom at 12 months. Drop attacks were reduced significantly in 77%. If pharmacotherapy fails, these two surgical approaches in combination or coupled with dietary therapy may be reasonable options.

Creating a treatment algorithm capable of guiding a provider through treatment options for patients with LGS, a complex and heterogeneous severe epilepsy, remains a challenge. However, we present an example workflow that the practitioner may use as a framework (Figure 6). We recommend strongly considering clobazam, topiramate or rufinamide initially based on efficacy and side effect profiles. Lamotrigine or felbamate may be effective, but caution should be exercised regarding potential exacerbation of myoclonic seizures and small risk of Stevens-Johnson syndrome in the former and potential life-threatening adverse reactions in the latter. Levetiracetam and valproate remain common choices, but strong supportive data are lacking. Finally, it is reasonable to pursue potential surgery options and dietary or medication therapies after failure of two or more antiseizure medications.

**Investigational and other therapies**

Currently approved antiseizure therapies have failed to provide long-lasting seizure control for most individuals with LGS. Therapies under investigation include cannabinoids, fenfluramine and transcranial direct current stimulation. Cannabidiol (CBD) is one of the two major neuroactive compounds in cannabis and has been the subject of intense interest as a new therapeutic option for patients with LGS. The antiseizure mechanisms of CBD are not definitively known, although studies have implicated G-coupled protein receptor protein 55 (GPR55), transient receptor potential of melastatin type 8 or ankyrin type 1 channels, the 5-HT$_{1A}$ receptor or the alpha3 and alpha1 glycine receptors as playing a role in reducing neuronal excitability.
Several parental surveys demonstrated a perceived decrease in seizures of >50% in over 80% of individuals with LGS after administering CBD-enriched compounds with good tolerability.\textsuperscript{72–74} Based on these basic science and anecdotal data, recent open-label and phase 3 studies have been conducted utilizing Epidiolex, a purified CBD extract from the marijuana plant. Efficacy data from the open-label add-on study evaluated 30 individuals with LGS of 137 total patients with epilepsy.\textsuperscript{75} Post hoc analysis of this subgroup revealed a median reduction of 37% in motor seizures and 37% of patients had a 50% reduction in total seizures. Drop seizures were reduced by a median of 69% in the 14 patients with atonic seizures. Common adverse events in 10% of subjects included somnolence, diarrhea, fatigue and anorexia and serious adverse events possibly related to CBD use occurred in 12%. Of 162 (3%) patients, 5 discontinued treatment due to adverse events.

Data from a recent randomized, double-blind, placebo-controlled trial of CBD as add-on therapy in 171 individuals with LGS demonstrated further promising results.\textsuperscript{76} During the treatment period after a 4-week titration, median reduction in total seizures was 45% vs 15% in the placebo group. Drop seizures were reduced by a median of 49% compared to 20% in the placebo group. Adverse events occurring in greater than 10% of patients included diarrhea, somnolence, pyrexia, decreased appetite and vomiting. Serious adverse events occurred in 23% of patients on CBD (vs 5% on placebo) and led to withdrawal in 14% in the CBD group (vs 1% on placebo).

Pharmacokinetic data and post hoc analysis of data from the open-label study implicate an interaction between CBD and clobazam, with possible synergy. CBD inhibits CYP2C19, which increases the concentrations of the antiseizure metabolite, N-desmethyl clobazam.\textsuperscript{77} A greater number of patients taking this combination demonstrated a 50% reduction in motor seizures (51% on combination therapy vs 27% in patients not taking clobazam). Although there may be synergy between these two drugs, concerns arose if one of the main reasons for the overall positive results is due to increasing N-desmethyl clobazam levels. Valproate and CBD may also synergize both in treatment and adverse events. More patients taking the combination of valproate and CBD also had a >50% reduction in seizures compared to other medication combinations (54% vs 33%, respectively), although this finding was not significant after multiple logistic regression analysis.\textsuperscript{79} Recent data revealed increases in aspartate aminotransferase and alanine aminotransferase in 28% of patients treated with CBD, 80% of whom were taking

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**Figure 6** Proposed management of Lennox-Gastaut syndrome.

**Notes:** First-tier preferred medications are in bold. *Commonly used medications without level 1 or 2 evidence.

**Abbreviations:** CC, corpus callosotomy; EEG, electroencephalogram; VNS, vagal nerve stimulator.

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Itself. In fact, we often encourage all patients with epilepsy to be allowed to participate in all regular activities as tolerated with the only real restriction of lifeguard supervision whenever in water or swimming. We, the expert clinicians, need to work and communicate better and more with these groups of people who care for the patients for many hours each day.

Conclusion

LGS remains an incredible therapeutic challenge for practitioners and poses immense risk and morbidity for afflicted individuals well into adulthood. Diverse etiologies, transient response to current therapies and various seizure types persistently create obstacles to lasting relief from epilepsy. Comparative data regarding therapeutic options are nonexistent, but several medical treatments are substantiated by high-level evidence and may provide relief in combination. Dietary therapy and epilepsy surgery may palliate the disease and rarely provide seizure freedom. Novel pharmacologic and noninvasive neurophysiologic therapeutic approaches are currently in both early- and late-stage development and may provide further relief from symptoms. CBD works for the treatment of seizures, although apparently not dramatically better than any of the currently other available treatments; it will likely obtain FDA approval soon. This medication will be widely used and sought after, and it is our belief that many patients and families who are antidrugs view this as an alternative, natural therapy. Furthermore, there are major financial and business implications with the earliest studies on plant extract CBD, while at least one other company is generating synthetic CBD. Ultimately, direct comparative data are desperately needed to guide best practice for these patients.

Disclosure

Yu-Tze Ng, MBBS, is on the Advisory Boards of Mallinckrodt Pharmaceuticals, Inc., Eisai Inc., Lundbeck Inc. and Zogenix Inc. and the Speakers’ Bureaus of Sunovion Pharmaceuticals, Inc., Lundbeck, Inc., Cyberonics Inc., UCB Pharma and Eisai Inc. The authors report no other conflicts of interest in this work.

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