

Cyclin-dependent kinase-like 5 (CDKL5) deficiency disorder: clinical review

Heather E. Olson¹ Scott T. Demarest², Elia M. Pestana-Knight³, Lindsay C. Swanson¹, Sumaiya Iqbal^{4,5}, Dennis Lal^{4,6}, Helen Leonard⁷, J. Helen Cross⁸, Orrin Devinsky⁹, Tim A. Benke¹⁰

¹ Department of Neurology, Division of Epilepsy and Clinical Neurophysiology, Boston Children's Hospital, Boston, MA, USA

² Children's Hospital Colorado and Department of Pediatrics, University of Colorado, School of Medicine, Aurora, CO, USA

³ Cleveland Clinic Neurological Institute Epilepsy Center, Cleveland Clinic Neurological Institute Pediatric Neurology Department, Neurogenetics, Cleveland Clinic Children's, Cleveland, OH.

⁴ Stanley Center for Psychiatric Research, Broad Institute of MIT and Harvard, Cambridge, MA, USA

⁵ Analytic and Translational Genetics Unit, Massachusetts General Hospital, Boston, MA, USA

⁶ Cleveland Clinic Genomic Medicine Institute and Neurological Institute, Cleveland, OH, US

⁷ Telethon Kids Institute, University of Western Australia, Perth, WA, Australia

⁸ UCL Great Ormond Street NIHR BRC Institute of Child Health, London, UK

⁹ Department of Neurology, NYU Langone Health, New York, NY

¹⁰ Children's Hospital Colorado and Departments of Pediatrics, Pharmacology, Neurology and Otolaryngology, University of Colorado, School of Medicine, Aurora, CO, USA

Corresponding author:

Heather Olson, MD, MS

Boston Children's Hospital

300 Longwood Ave., Mailstop 3063

Boston, MA 02115

Heather.Olson@childrens.harvard.edu

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Abstract

CDKL5 deficiency disorder (CDD) is a developmental encephalopathy caused by pathogenic variants in the gene cyclin-dependent kinase-like 5 (*CDKL5*). This unique disorder includes early infantile onset refractory epilepsy, hypotonia, developmental intellectual and motor disabilities, and cortical visual impairment. We review the clinical presentations and genetic variations in CDD based on a systematic literature review and experience in the CDKL5 Centers of Excellence (COEs). We propose minimum diagnostic criteria. Pathogenic variants include deletions, truncations, splice variants, and missense variants. Pathogenic missense variants occur exclusively within the kinase domain or affect splice sites. The CDKL5 protein is widely expressed in the brain, predominantly in neurons, with roles in cell proliferation, neuronal migration, axonal outgrowth, dendritic morphogenesis and synapse development. The molecular biology of CDD is revealing opportunities in precision therapy, with phase 2 and 3 clinical trials underway or planned to assess disease specific and disease modifying treatments.

Key words: CDKL5 deficiency disorder; developmental encephalopathy; epileptic encephalopathy; epilepsy genetics; clinical trials

Abbreviations: CDKL5 – Cyclin dependent kinase-like 5; CDD – CDKL5 deficiency disorder; COE – International Foundation for CDKL5 Research Center of Excellence

Introduction

Pathological variants in cyclin-dependent kinase-like 5 (*CDKL5*)¹⁻⁵ cause CDKL5 deficiency disorder (CDD, OMIM 300203, 300672), a developmental encephalopathy (DE).⁶ DEs share common constellations of features that extend beyond traditional criteria of autism spectrum disorder or intellectual disability such as treatment resistant epilepsy, movement disorders and autonomic dysfunction. Pathological variants in *CDKL5* cause early-life epilepsy in 1 in 40,000 - 60,000 live births,⁷⁻⁹ half to a third as prevalent as Dravet (1:20,000-50,000)^{10,11} or Rett (1:10,000 females)¹² syndromes. Common features include infantile-onset refractory epilepsy, hypotonia, developmental delay, intellectual disability and visual impairment.¹³⁻¹⁵ CDD is an X-linked disorder that affects females more than males (~4:1)¹⁶ as males with germline variants have no normal *CDKL5* gene and may not survive fetal life. CDD was initially identified as the early seizure variant of Rett syndrome, but only 23.7% of females and no males with CDD met criteria for typical or atypical Rett syndrome and diagnosis of atypical Rett syndrome is even rarer in recent clinical experience.^{13,16,17}

The literature on CDD includes case series and data from the International CDKL5 Disorder Database, based on caregiver questionnaires.^{13,18-22} Prospective data collection is occurring through the Natural History Study for Rett and Rett-related disorders (U54 HD061222; ClinicalTrials.gov: NCT00299312/NCT02738281) and through a clinic based study by the International Foundation for CDKL5 Research (IFCR) Centers of Excellence (COEs). Initial sites were Boston Children's Hospital, Children's Hospital Colorado and Cleveland Clinic. The COEs provide comprehensive care and collaborate on research for CDD. The COEs have

collected data on > 93 individuals with CDD between 0 to 34 years to inform the typical features and spectrum of CDD.¹⁶

CDKL5 protein and molecular biology

CDKL5 is a serine/threonine kinase. The N-terminal catalytic domain starts in exon 2 and the long C-terminus may have a regulatory role.²³ CDKL5 is highly expressed in the brain, predominantly in neuronal nuclei and dendrites, with peak expression in early postnatal life, when symptoms typically begin.²⁴⁻²⁷ The CDKL5 protein has roles in cell proliferation, neuronal migration, axonal outgrowth, dendritic morphogenesis and synapse development and function in the adult brain.²⁸

CDKL5 has multiple transcripts due to alternative splicing in mice and humans.²³ The primary brain isoform is hCDKL5_1.²³ Pathogenic missense variants occur exclusively within the catalytic domain except for the recurrent missense variant p.Val718Met which affects splicing.²⁹ A male individual mosaic for this variant followed in our COEs has a “typical” CDD phenotype but has walked independently since the age of 2 years. Somatic mosaicism in probands, perhaps more often in males, and presumed parental mosaicism is described; unaffected parents with a full germline *CDKL5* variant have not been described.^{15,20,30-34} Thus, parental testing is critical to assess variants of uncertain significance in *CDKL5*. There are no biomarkers nor is there a functional assay for variants of uncertain significance; both would be beneficial to the field.

Currently, no evidence supports pathogenic variants in exons 20, 21, and 22 which are part of transcript isoform *hCDKL5_5*, or within exon 17 which is part of transcript isoform *hCDKL5_2*.²⁹ The pathogenicity of variants in the 5' UTR remain uncertain except for deletions extending to include exons 1 and 2.²⁹ Deletions and truncating variants appear to nearly universally cause CDD.²⁹ *CDKL5* variants from individuals in the COEs are shown in Figure 1, on a schematic of the protein and on a 3D model along with population variation.

Individuals with *CDKL5* duplications show variable penetrance of macrocephaly and learning disability without epilepsy or magnetic resonance imaging (MRI) abnormalities.³⁵ Neighboring genes are rarely affected in these duplications. This contrasts with other genetic developmental encephalopathies for which duplications cause a different disease than deletions (e.g., *MECP2* and *FOXG1* disorders).^{29,36-39} More comprehensive phenome-genome studies of *CDKL5* duplication are needed to determine if these duplications are clinically pathogenic.

Molecular studies in rodent models have identified several pathways are altered in CDD, including the AKT/mTOR, AKT/GSK-3 β and BDNF-Rac1 signaling pathways and the NGL-1-PSD95 interaction.^{24,25,27,28,40,41} However, these rodent models demonstrate a behavioral phenotype but lack spontaneous seizure activity.⁴¹⁻⁴³ Dendritic outgrowth and spine development are inconsistently altered in cellular CDD models.⁴¹ Mouse model data suggests that CDKL5 expression modulates post-synaptic localization and composition of NMDA receptors.⁴⁴ CDKL5 influences MeCP2 activity, possibly explaining overlapping features of

CDD with Rett syndrome, although the relevance of this *in vitro* data remains uncertain.²⁸ Additional CDKL5 substrates include DNMT1, AMPH1, NGL-1, HDAC4, MAP1S, ARHGAP2 and EB2.^{45,46} A recent review summarized the molecular features of CDD.²⁸

Epilepsy and treatment

Refractory epilepsy severely impacts quality of life and neurodevelopment.^{14,47} Median age of epilepsy onset is 6 weeks with 90% onset by 3 months.^{13,14} Eighty percent of children with CDD have daily seizures and 20% have weekly to monthly seizures.⁴⁸ Less than half (43.6%) of caregivers reported >2 month of sustained seizure freedom.^{14,47} Among individuals with more than 2 months of seizure freedom (N=71 of 163 families reporting information on seizure freedom), in three quarters of families able to provide additional information this honeymoon period had a median duration of 6 months (range 2.5 months to 6 years) and median onset of 2 years.¹⁴ In the COE cohort, 9% of families reported a seizure free period of 1-3 months, 12% 3-6 months, 11% 6-12 months and 13% >12 months. This honeymoon period typically occurs in the first 2 years of life, though some have seizure free periods later in childhood or into their teenage years.¹⁶

Three proposed epilepsy stages in CDD include: 1) early onset, at times pharmaco-responsive, 2) epileptic encephalopathy and 3) refractory multifocal and myoclonic epilepsy.⁴⁹ Infantile spasms are the initial seizure type in 23%, and present at any point in 81% of individuals with CDD.^{16,50} Evolving epilepsy tends to be generalized or mixed focal and generalized with spasms, tonic, and tonic-clonic seizures most common.^{16,50} Complex seizure semiology with multiple phases per seizure is common (56%),^{16,50} including a novel seizure pattern: hypermotor-tonic-spasms sequence.^{17,51-54} Autonomic changes can be seen intermixed with any of these seizure types, including pupillary dilation, facial flushing, irregular respirations, apneas or hyperventilation.¹⁶ While for many individuals refractory epilepsy continues long term, our experience suggests that rare individuals outgrow their epilepsy in childhood and one individual did not have epilepsy onset until 9 years of age (*de novo* c.1675C>T; p.Arg559Ter).¹⁶

Electroencephalograms (EEGs) at onset ranged from hypsarrhythmia to mild abnormalities but more abnormalities in background rhythms and epileptiform activity develop over time.^{15,18,20,49,53,55,56} Early mild abnormalities that sometimes precede a diffuse encephalopathy included focal delta slowing in the posterior head regions and intermittent generalized slowing.⁵⁷ Some individuals have hypsarrhythmia and evolution often includes focal or generalized slowing, focal and/or generalized epileptiform activity, and in some cases pseudoperiodic epileptiform discharges.^{15,18,20,49,53,55,56} Infantile spasms can occur however in the absence of hypsarrhythmia, including with a normal EEG or rare epileptiform activity.^{16,57} Burst suppression is rare and atypical for neonates with CDD.⁵³

Data on the efficacy of seizure therapies is limited. A review of anti-seizure medication response in 39 individuals with CDD found a responder rate (defined as 50% seizure reduction) to at least

one anti-seizure medication of 69% at 3 months, 45% at 6 months and falling to 24% at 12 months.⁵⁸ Medications with the highest rates of seizure reduction at 3 months included felbamate, vigabatrin, clobazam, valproic acid, steroids, lamotrigine and zonisamide.⁵⁸ The efficacy of each anti-seizure medication showed large inter-individual variability, with a maximum of 33%, except for felbamate with 3/3 responding at 3 months.⁵⁸ At 12 months, the responder rate dropped to 0-20% except for 1/3 (33%) still responding to felbamate.⁵⁸ Exacerbation of seizures occurred with at least one anti-seizure medication in 31% of individuals; most often with carbamazepine (4/15 individuals).⁵⁸ Our approach in the COEs is to use broad spectrum anti-seizure medications especially when there are generalized seizure types. Overall, 2/39 individuals (5%) became seizure free for >3 years with anti-seizure medication or ketogenic diet.⁵⁸ The most commonly used anti-seizure medications in CDD were broad spectrum, including clobazam, valproate, topiramate, levetiracetam and vigabatrin and 29.6% of individuals were treated with steroids or ACTH.¹⁴ Another study of caregiver perceptions of treatment by survey of 44 individuals with CDD/families reported subjective efficacy (not further defined) in more than 2 individuals to vigabatrin (12/23), clobazam (6/14), sodium valproate (5/27), and levetiracetam (3/27).⁵⁹ In the Boston Children's Hospital COE, > 50% reduction in seizure types (excluding epileptic spasms) in more than one individual occurred with the following anti-seizure medications: phenobarbital, clobazam, topiramate, rufinamide and valproic acid.¹⁶

Infantile spasms in individuals with CDD are often refractory to first-line therapies. From the parent-entered International CDKL5 Disorder Database, infantile spasms were reported in 33.8% of individuals.¹⁴ By contrast, in the COE cohort of 93 individuals with data derived from physicians, spasms occurred in 81% (n=75).⁵⁰ We hypothesize that the difference in prevalence may result from data collection methods and possible under-diagnosis of infantile spasms if not associated with hypsarrhythmia. Among 18 individuals in the COE cohort with detailed data, median spasm onset was age 4 months (2 weeks to 36 months);⁶⁰ spasms resolved in only 3/18 individuals (17%) with first line treatments (ACTH or vigabatrin) for epileptic spasms, lower than the ~ 46% response rate at 3 months observed in infantile spasms cohorts.^{60,61} Since CDD is often diagnosed before spasm onset and other seizure types often occur before spasms, such individuals with CDD are candidates for novel therapies.^{49,61-65}

The ketogenic diet has modest efficacy in treating epilepsy in CDD. The largest cohort reported 104 individuals with CDD treated with median ketogenic diet duration of 17 months and reductions in seizure frequency in 61/104 (58.7%), consistent with data from the Boston Children's Hospital COE.^{16,66} Side effects of the ketogenic diet occurred in 31.7% of individuals.⁶⁶ A smaller cohort of 12 individuals with CDD reported that 2 (17%) had a significant reduction in seizures for >6 months and 1 (8%) for >1 year.⁵⁸ Behavior improvements were reported including improved alertness in 19/104 (18%) on the ketogenic diet while worsening motor skills and social interactions were reported in 5.8%.⁶⁶ Ketogenic diet was most often discontinued due to lack of long-term efficacy. These retrospective observational reports

did not provide data on diet ratios, ketone levels, efficacy for different seizures types, percent reduction in seizures, or duration of efficacy. Notably, few individuals were treated with ketogenic diet in the first year of life and its efficacy and tolerability in this CDD group remains unknown.

Palliative surgeries for refractory epilepsy include vagus nerve stimulation (VNS) and corpus callosotomy. Among 220 individuals with CDD with parent-entered data, 17% had a VNS implanted and 69% of parents reported reduced seizure frequency.⁶⁷ These data are consistent with a case report of benefit⁶⁸ and Boston Children's Hospital COE reports improvement in 5/6 individuals.^{16,69} There are no reports of response to corpus callosotomy in the literature and limited experience in the COEs but no response in one individual.¹⁶ In the International CDKL5 Disorder Database at least 7/10 individuals had some improvement in seizures following corpus callosotomy of whom two had a longer than 6 month period of seizure freedom (unpublished data).

Development

All individuals with CDD have severe global developmental delays and intellectual disability, though regression is rare except with worsening of seizures or epileptic encephalopathy.^{13,15,18-20,70-73} Individuals with CDD achieve gross motor milestones at a slowed pace compared to normal. Assessing in girls for whom there are more data, independent walking was attained by 22-23%, raking grasp by 49% by 5 years and pincer grasp by only 13% at any time point.^{47,71} Using time to event analysis, just under half of individuals could babble by 6 years (43/97 or 44%), and just under a quarter of subjects could speak single words by 7 years of age (17/105 or 16%).⁴⁷ Spoken language, signs or abstract symbols were produced by 26% of females with CDD (0% of males) and 7.5% of females with CDD spoke in sentences.⁷¹ The most common communication modalities were body language, facial expressions, and simple sounds and gestures.⁷¹ Use of non-verbal communication devices such as switches and eye gaze technology based communication is often limited by cortical visual impairment, but can be used by some individuals with CDD.¹⁶ Autistic features are commonly reported but autism spectrum disorder is infrequently diagnosed due to global developmental impairments.^{15,18-21,73-76} A diagnosis of autism spectrum disorder has been observed rarely in the COEs.⁶⁰ Overall, males were reportedly more severely affected than females, though our COE experience does not suggest a striking difference in phenotype.^{13,16,47} Males can have a milder phenotype.¹⁶

Movement disorders

Hand stereotypies were reported in 80% of individuals, and 59% of females and 12.5% of males achieve functional hand use which may be limited by stereotypies.¹³ The hand stereotypies that we have observed are more consistent with self-stimulatory behavior versus the type of hand stereotypies observed in Rett syndrome.¹⁶ Repetitive leg crossing is also commonly observed.¹⁶ We lack data on other movement disorders although the COEs have observed episodic or

persistent, and occasionally severe, choreoathetosis, akathisia, dystonia, and parkinsonian features.¹⁶ Movement disorders may worsen when individuals achieve temporary seizure control.¹⁶ At times this may be attributed to polytherapy with anti-seizure medications, improving with reduction in number of anti-seizure medications.¹⁶

Physical exam findings

Hypotonia is a nearly universal feature.^{14,15} Cortical visual impairment is common, occurring in at least 75% of individuals,¹⁶ with reports of poor eye contact and lack of visual tracking with an otherwise normal ophthalmologic exam.^{15,17,18,20,47,72,73} Rotatory and horizontal nystagmus, dysconjugate gaze, abnormal fixation, and reduced or absent optokinetic nystagmus (OKN) response are features observed in individuals with visual impairment. Microcephaly and deceleration of head growth occurs in less than 10% of individuals.^{13,15,18-21,72,73} Subtle dysmorphic features include deep set eyes, broad or high forehead, prominent lips, deep philtrum, puffy phalanges and tapered fingers.^{13,15,20,70,73,74} Movement disorders have also been observed as above.

Neuroimaging

Neuroimaging has not yet been systematically reported in individuals with CDD, although case reports document normal brain anatomy or less often, show cortical atrophy or T2/fluid attenuated inversion recovery hyperintensities in the white matter.^{15,18-20,49,53,55,56,70,72,73,75,77}

Neuropathology findings

There is very little literature describing the neuropathological findings in individuals with CDD. One case report described the brain as the sole organ with abnormalities in a post mortem examination.⁷⁸ In addition to brain and cerebellar atrophy and ventricular enlargement, microscopic examination of the brain revealed gliosis in the cerebral cortex with preservation of the hexalaminar layers, neuronal heterotopias in the white matter of the cerebellar vermis and gliosis of the cerebellar cortex with loss of Purkinje cells and axonal torpedoes.⁷⁸ Perivascular lymphocytes and axonal swelling in the anterior horn were the main findings in the spinal cord.⁷⁸ This child had a pathogenic splice variant c.2277-2A>G, predicted to destroy the splice acceptor site of exon 16.⁷⁸

Other comorbidities

Gastrointestinal symptoms were reported by parents in up to 86.5% in the International CDKL5 Disorder Database (122/141), most often constipation (70.9%), reflux (64.1%), or air swallowing (27.1%).^{13,48} Orthopedic complications of hypotonia include scoliosis (68.5% by 10 years).^{13,48} Dysphagia is common and may require gastrostomy. While 79.3% of individuals with CDD in the International CDKL5 Disorder Database fed orally and 20.7% were exclusively fed by gastrostomy or nasogastric tube, some required supplemental tube feedings and only 5.3% were

able to eat and drink independently.⁴⁸ Notably, ~33% of individuals treated with the ketogenic diet had a gastrostomy; a similar percentage, 11/36 (31%), had gastrostomy in a caregiver survey of individuals with CDD.⁶⁶ Sleep difficulties are very common, reported by parents in over 85% of individuals, sometimes dubbed “all night parties.”^{13,48} Night waking was reported in 72/123 individuals (58.5%).⁴⁸ The odds of sleep problems were highest in the 5-10 year age group compared to those aged less than 5 years.⁴⁸ Using the Child Health Sleep Questionnaire (CSHQ), the team at Children’s Hospital Colorado found significantly abnormal sleep maintenance and duration.⁷⁹ Abnormal sleep duration was reported in 63% of individuals with CDD compared to age based norms, and the mean score for waking once per night and more than once per night were elevated (2.45 and 2.25 respectively, $p < 0.001$ for both).⁷⁹ Breathing abnormalities include hyperventilation reported in 13.6% of individuals, breath holding in 26.4%, and aspiration in 22.6%.⁴⁸ Parents have expressed concerns about cardiac arrhythmias, and one study by caregiver survey reported arrhythmia in 11/29 individuals with CDD who underwent ECG.⁵⁹ Arrhythmias have not however been confirmed in the COEs, and this is an area of current investigation.¹⁶ Sudden unexpected death in epilepsy (SUDEP) may occur but in large cohorts the frequency of CDD is much lower than Dravet syndrome or *SCN8A*- related epilepsy given the frequencies of these disorders.⁸⁰⁻⁸² However, the high seizure frequency and severity suggests that individuals with CDD are at high risk of SUDEP, with daily and often nocturnal tonic or tonic-clonic seizures.⁸³ Metabolic abnormalities are rare; a boy with CDD had transient methylmalonic acidemia but the concurrence may be coincidental.⁸⁴

Clinical criteria

We propose minimum CDD diagnostic criteria to include a pathogenic or likely pathogenic variant in the *CDKL5* gene along with motor and cognitive developmental delays and epilepsy with onset in the first year of life. We recognize that some patients with *CDKL5* deficiency may be atypical and not meet these formal criteria. Table 1 includes a list of common clinical features and what we determine to be the minimum diagnostic criteria.

Genotype-phenotype correlations

Genotype-phenotype correlations are limited. Compared to individuals with truncating variants, those with pathogenic missense variants in the ATP binding site had a milder disorder, some with ability to walk unaided, better hand use, and less refractory epilepsy.⁸⁵ One individual in the COE cohort with a missense variant, p.Tyr24Cys, in the ATP binding site has refractory epilepsy but is making more developmental progress than most individuals with CDD and lacks cortical visual impairment. Another study found that females with late truncating variants after amino acid 781 had better gross motor, hand function and communication milestones than earlier truncating variants.^{47,71} Seizure frequency was lower in individuals with truncating variants between amino acid 172 and 781 compared to those with no functional protein (incidence rate ratio 0.57; 95% confidence interval 0.35 – 0.93).¹⁴ The influence of somatic *CDKL5* mosaicism on clinical phenotype is unknown.

Clinical trials and treatments suggested from animal studies

The ultimate goal of understanding the genetics and molecular biology of CDD is to establish precision therapies, targeting the underlying biologic pathways, although the complex biology of CDD makes this challenging. This may include small molecules or perhaps genetic/genomic treatment approaches. The hope is that these therapies may be more effective than currently available treatments.

An open label phase 2 clinical trial of cannabidiol in CDD and three other early life genetic epileptic encephalopathies suggested improvement in frequency of motor seizures >3 seconds in duration.⁸⁶ The CDD group had a median reduction in motor seizures from median 66.4 per 28 days [IQR 25.9 – 212.0] to 35.8 [IQR 8.9 – 141.6] at 12 weeks, with stable frequency at 48 weeks.⁸⁶

A phase 2 randomized, placebo-controlled crossover study of Ataluren, a medication that targets pathogenic nonsense variants in other genetic diseases, is in process in CDD (NCT02758626) but results are not yet available. Another phase 2 trial is being initiated for TAK-935, a novel medication that modulates the NMDA receptor system (NCT03694275).

Allopregnanolone (Ganaxolone) is a neurosteroid, for which there have been previous trials in the epilepsies including for infantile spasms, status epilepticus and PCDH19 related epilepsy. A phase 2 open-label clinical study is completed, and a phase 3 randomized, placebo-controlled study is ongoing in CDD (NCT03572933). *CDKL5* regulates the interaction of IQGAP1 with microtubule plus end tracking protein CLIP170, disrupting microtubule dynamics in CDD.⁸⁷ Allopregnanolone restores microtubule association of CLIP170 in *CDKL5* deficient neurons, rescuing morphological defects.⁸⁷

Molecular pathway abnormalities in CDD rodent models suggest additional possible therapies. Dysregulation in the GSK3-beta pathway in *Cdkl5* knockout mouse model led to treatment with a GSK3-beta inhibitor, Tideglusib.⁴⁰ Treatment during the juvenile period improved hippocampal development and hippocampus-dependent behaviors, whereas treatment in adult mice was not beneficial. Reduced expression of the GluA2 subunit of the AMPA-R was identified in *CDKL5* knockout mice.⁸⁸ Treatment of the mice with the antidepressant tianeptine normalized the expression of membrane inserted AMPA-Rs containing GluA2.⁸⁸ Treatment of rodents with IGF-1, which activates the AKT/mTOR pathway, rescued dendritic spine instability.⁸⁹

Protein substitution therapy has been evaluated in animal models with promising results, though feasibility and timeframe to bring this approach to human trials is uncertain.⁹⁰ Novel therapeutic approaches including genome editing, RNA-based therapeutics and gene therapy are being strongly considered.

Conclusions

The “typical” individual with CDD, defined by having a pathogenic gene variant that impairs CDKL5 function, is characterized by onset of treatment-resistant epilepsy and severe cognitive and motor developmental delays. Epilepsy usually begins in the first three months of life and includes tonic seizures, epileptic spasms without hypsarrhythmia, a seizure-free honeymoon period around 1-2 years old that may last up to 12 months, followed by multiple (2+) seizure types including sequences of mixed seizure type; cortical visual impairment associated with rotatory or horizontal nystagmus, dysconjugate gaze and abnormal fixation; global motor delays with hypotonia and severe impairment of hand function. Permanent regressions or progressive deterioration of neurological function is rare. Other commonly associated features of individuals with CDD include dyskinetic movements, sleep disturbances, autonomic and breathing disturbances, and GI disturbances. We propose minimum CDD diagnostic criteria as above recognizing that some individuals with CDKL5 deficiency may be atypical and not meet these formal criteria.

CDD is an epileptic encephalopathy, defined by the International League Against Epilepsy as a disorder in which “the epileptic activity itself may contribute to severe cognitive and behavioral impairments above and beyond what might be expected from the underlying pathology alone and that these may worsen over time”.⁹¹ The transient regressions that occur in CDD are consistent with this definition although there is undoubtedly a developmental component as well. Future studies of the natural history of CDD will better define the role of seizures, interictal epileptiform activity, and anti-seizure medications as factors that may adversely affect these children. We hope that increased preclinical studies to define the molecular consequences of impaired CDKL5 and advances in novel, targeted drug development and molecular biology and genetic approaches will radically transform the prognosis for children with CDD.

Figure 1. A) A schematic of the CDKL5 protein with variants from individuals with CDD evaluated in the CDKL5 Centers of Excellence. *CDKL5* gene image adapted from prior publication.⁴⁷ B) 3D protein structure of the *CDKL5* gene (Protein Data Bank ID: 4bgq) along with position of population variation (blue spheres) from gnomAD database and variants from the COEs (red spheres). C) Highlight of variants in functional domains in the CDKL5 protein. The missense variants in *CDKL5* identified in affected individuals are mapped on the 3D protein structure (protein data bank id: 4bgq) as red spheres (total 23 positions). The yellow-colored region is a nucleotide binding region (aa. 19 - 72) and we observed the disease-associated variant p.Tyr24Cys in this region. The cyan-colored site is a proton acceptor active site (aa. 135) and we observed the disease-associated variant p. Asp135Gly in this site. The green-colored region is a functionally essential DFG motif (aa. 153 - 155) and we observed the disease-associated variant p. Asp153Val in this region. The pink-colored region is the morphology (information content) or consensus sequence of phospho-Tyrosine Y171 (part of Thr-Glu-Tyr motif) (aa. 164 - 178) and we observed the disease-associated variants p.Trp176Arg, p.Tyr177His, p.Arg178Gln in this region.

Table 1. Common clinical characteristics and proposed minimal diagnostic criteria.

Common clinical characteristics	Proposed minimal diagnostic criteria
<ul style="list-style-type: none"> • Epilepsy, early onset and refractory • Severe global developmental delay • Intellectual disability • Hypotonia • Cortical visual impairment • Sleep disturbance • Dyskinetic movements, • Autonomic and breathing disturbances • GI disturbances (reflux, constipation) • Dysphagia 	<ul style="list-style-type: none"> • A pathogenic or likely pathogenic variant in the <i>CDKL5</i> gene • Motor and cognitive developmental delays • Epilepsy with onset in the first year of life

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