De Novo Pathogenic Variants in CACNA1E Cause Developmental and Epileptic Encephalopathy with Contractures, Macrocephaly, and Dyskinesias


Developmental and epileptic encephalopathies (DEEs) are severe neurodevelopmental disorders often beginning in infancy or early childhood that are characterized by intractable seizures, abundant epileptiform activity on EEG, and developmental impairment or regression. CACNA1E is highly expressed in the central nervous system and encodes the α1 subunit of the voltage-gated CaV2.3 channel, which conducts high voltage-activated R-type calcium currents that initiate synaptic transmission. Using next-generation sequencing techniques, we identified de novo CACNA1E variants in 30 individuals with DEE, characterized by refractory infantile-onset seizures, severe hypotonia, and profound developmental impairment, often with congenital contractures, macrocephaly, hyperkinetic movement disorders, and early death. Most of the 14, partially recurring, variants cluster within the cytoplasmic ends of all four S6 segments, which form the presumed CaV2.3 channel activation gate. Functional analysis of several S6 variants revealed consistent gain-of-function effects comprising facilitated voltage-dependent activation and slowed inactivation. Another variant located in the domain II S4-S5 linker results in facilitated activation and increased current density. Five participants achieved seizure freedom on the anti-epileptic drug topiramate, which blocks R-type calcium channels. We establish pathogenic variants in CACNA1E as a cause of DEEs and suggest facilitated R-type calcium currents as a disease mechanism for human epilepsy and developmental disorders.

Introduction

Developmental and epileptic encephalopathies (DEEs) are clinically and genetically heterogeneous severe neurodevelopmental disorders. These conditions often start in infancy or early childhood and are characterized by intractable seizures, frequent epileptiform activity on EEG, and developmental slowing or regression.1 A genetic etiology can be identified in upward of 30% of individuals with DEE, predominantly de novo variants in genes encoding neuronal ion channels or proteins involved in synaptic transmission.2 Voltage-gated calcium channels mediate the influx of calcium in response to membrane depolarization in excitable cells. In presynaptic nerve terminals, this calcium influx triggers transmitter release for synaptic transmission. Several neurological and cardiac disorders are caused by pathogenic variants in genes encoding α1 subunits of voltage-gated calcium channels, including CACNA1A (MIM: 601011) (familial hemiplegic migraine [MIM: 141500], episodic ataxia [MIM: 108500], and epilepsy [MIM: 617106]),3–5 CACNA1C (MIM: 114205) (Timothy syndrome [MIM: 601005]),3–5 CACNA1D (MIM: 114206) (primary aldosteronism, neurodevelopmental disorders

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The functionally critical a1E-subunit of the CaV2 family member CaV2.3, which is widely expressed throughout the central nervous system and conducts high-voltage-activated, rapidly inactivating R-type calcium currents,9–11 are expressed in rodent models of acquired epilepsy,12–15 and a recent meta-analysis of whole-exome sequencing data of nearly 7,000 individuals with neurodevelopmental disorders implicates CACNA1E as a possible candidate gene.16 However, in contrast to the other a1-subunits, pathogenic variants in CACNA1E have not been established as disease causing in humans.17

Here, we clinically and functionally characterize a disorder of neuronal calcium channel dysfunction, caused by de novo missense variants in CACNA1E. We report 30 individuals who present with a spectrum of severe early-onset neurodevelopmental disorders characterized by severe to profound global developmental delay, significant hypotonia, and developmental and epileptic encephalopathy.
Subjects and Methods

Study Participants
This study was approved by the local institutional review boards of the participating centers. Informed consent for participation in this study was provided by all parents or legal guardians of minors or individuals with intellectual disability. Individuals with likely pathogenic CACNA1E variants were ascertained between June 2015 and May 2018 via an international collaborative network of research and diagnostic sequencing laboratories. Some participants were identified via GeneMatcher. Individual 16 was ascertained from the Epilepsy Panel Study. Individuals 23 and 26 were ascertained from the Deciphering Developmental Disorders Study. Individual 31 was ascertained from the UK National Institute for Health Research (NIHR) Bioresource for Rare Diseases. The remaining participants were referred from collaborating researchers, clinicians, and diagnostic laboratories. Detailed medical history information, including developmental and epilepsy history, morphologic details, and neurological findings, was provided for each participant. Where required, reverse phenotyping was performed. Available brain imaging and EEG data were reviewed for all participants. Epilepsy syndromes and seizure types were classified according to the International League Against Epilepsy (ILAE) classification criteria.

Variant Identification and Interpretation

Whole-Exome Sequencing
Trio whole-exome sequencing (WES) was performed on a diagnostic basis at GeneDx for individuals 1, 5, 6, 11, and 25 as previously described, and at Ambry Genetics for individuals 13, 14, 20, and 29, and at ARUP Laboratories for individual 15 (Supplemental Subjects and Methods). Research-based trio WES was performed for individuals 3, 4, 7–9, 16–19, 21–23, 26–28, and 33. Individual 30 underwent WES as a mother-proband duo. Trio WES was performed as described previously for individual 16 as part of the Epilepsy Panel Study. Individuals 23 and 26 were ascertained by reanalysis of the data from the Deciphering Developmental Disorders Study as part of a local “Solving the Unsolved” project in Manchester (UK) and a Complementary Analysis Project #237. Trio WES was performed for individual 27 as described previously.

Sequencing methodology for the remaining participants is detailed in the Supplemental Subjects and Methods. All candidate variants identified via WES were validated by Sanger sequencing, except for the recurrent c.1054G>A (p.Gly352Arg) variant in individual 8.

Whole-Genome Sequencing
Research-based trio whole-genome sequencing (WGS) was performed in individuals 10, 24, and 31, as described in the Supplemental Subjects and Methods. Candidate variants identified via WGS were validated by Sanger sequencing.

NGS Panel Analysis
Individual 12 underwent diagnostic NGS-based 1430 gene epilepsy panel testing (GeneDx). Individuals 2 and 32 underwent research epilepsy panel testing, as previously described. The presence or absence of variants identified via epilepsy panel testing was confirmed via Sanger sequencing in participants and parents. Parental relationships were confirmed for individuals 2 and 12 by short tandem repeat analysis. Parental DNA samples were unavailable for individual 32.

Variant Interpretation
All identified CACNA1E variants were interpreted according to the American College of Medical Genetics and Genomics standards and guidelines for the interpretation of sequence variants. CACNA1E variants were considered likely pathogenic if they were confirmed to have occurred de novo in the affected individual with confirmed parental relationships and were not observed in a control cohort of 123,136 individuals in the Exome Aggregation Consortium (ExAC) or genome Aggregation Database (gnomAD).

Functional Analysis
Two laboratories independently investigated the effects of the domain II S6 and the domain II S4-S5 linker variants. Given the congruence of findings from these two groups, we combined the results into a single study. The two laboratories used different CaV2.3 channel backbones for mutagenesis and slightly different experimental setups and approaches. In each case, appropriate wild-type controls were used, and no direct statistical comparisons between the two datasets were made. Prior studies characterizing the structure and function of CaV2.3 channels had examined the biophysical and electrophysiological properties of several variants that were artificially introduced into S6 segments of CaV2.3 channels, including p.Arg352Gly, p.Ile701Val/Gly, and p.Ala1720Gly. These prior findings were also compared with the results of our functional analyses.

Mutagenesis
The human CaV2.3-subunit (z1E; GenBank: NM_001205293.1) in the pcDNA3.1 vector was kindly provided by Norbert Klugbauer (Institute for Experimental and Clinical Pharmacology and Toxicology, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany), whereas human CaV2.3 (z1E, GenBank: L29885.1) was provided by Dr. Toni Schneider (University of Cologne). The human ß2a-subunit cloned into a pciRES-EGFP-Vector (Clontech) was from Stefan Herzig (Department of Pharmacology, University of Cologne, Cologne, Germany). Site-directed mutagenesis was performed to engineer the domain II S6 segment variants into the human CaV2.3 channel (z1E, using the Q5-Site directed mutagenesis kit (New England Biolabs; primers are available upon request). To exclude incorrect ligation of the plasmid, a diagnostic restriction digest was performed. The p.Ile603Leu domain II S4-S5 linker variant was introduced into CaV2.3 (z1E, ß2a) channel in pcDNA3 using the QuickChange II XL Site-Directed Mutagenesis Kit (Agilent, Cat# 200525). In each case, the mutant cDNA was then fully re-sequenced before use in experiments to confirm the introduced variant and exclude any additional sequence alterations.

Transfection and Expression in tsA201 Cells
Human tsA201 cells, a transformed human kidney cell line stably expressing an SV40 temperature-sensitive T antigen (Sigma-Aldrich), were cultured at 37 °C, with 5% CO2 humidified atmosphere and grown in Dulbecco’s modified Eagle medium + 10% (v/v) fetal bovine serum. For the domain II S6 mutants, transfections using “TransIT-LT1” reagent (Mirus Bio) were performed for transient expression of wild-type or mutant z-subunits together with the ß2a-subunit. We transfected 3.16 μg of total DNA in a molar ratio of 1:1. Only cells with green fluorescence were used for electrophysiological recordings. For the domain II S6 variants, we performed electrophysiological recordings of tsA201 cells that were transiently transfected with either wild-type or mutant z1E-subunits together with the ß2a-subunit, confirmed by the green fluorescence of EGFP which was co-expressed via an internal ribosome entry site (IRES). For the domain II S4-S5 mutant and corresponding wild-type control, cells were transfected with CaV2.3 subunits.
and rat β1b and α2δ subunits (3 μg each) along with eGFP, using the calcium phosphate method.

**Electrophysiology**

Standard whole-cell recordings were performed using an Axopatch 200B amplifier, a Digidata 1320A or Digidata 1440A digitizer, and pCLAMP 8 or 10.2 data acquisition software (Molecular Devices). Leakage and capacitive currents were automatically subtracted using a pre-pulse protocol (-P/4) for the domain II S6 variants. Currents were filtered at 3 or 5 kHz and digitized at 10 kHz. All recordings were performed at room temperature of 21°C–23°C. The liquid junction potential was calculated to be at 10.3 mV using pCLAMP 10.4 software and was not corrected. Cells were visualized using an inverted microscope (Axio-Vert.A1, Zeiss or DM IL LED, Leica or Nikon TE2000). For investigation of the domain II S6 variants, the pipette solution contained (in mM): 2 CaCl₂, 137 CsCl, 1 MgCl₂, 10 HEPES (pH 7.4; 320 mOsm). For both solutions pH was adjusted with CsOH and osmolarity with Mannitol if necessary. Ba²⁺ currents of 0.4–4 nA were recorded from transfected tsA201 cells.

For the domain II S4-S5 variant and wild-type controls, external solutions contained in (mM): 2 CaCl₂, 137 CsCl, 1 MgCl₂, 10 HEPES, 10 glucose (pH 7.4 adjusted with CsOH) or 5 mM BaCl₂, 132.5 CsCl, 1 MgCl₂, 10 HEPES, 10 glucose (pH 7.4, adjusted with CsOH). The pipette solution contained (in mM): 130 CsCl, 2.5 MgCl₂, 10 HEPES, 10 EGTA, 1 ATP, 0.5 GTP (pH 7.4 adjusted with CsOH). Borosilicate glass pipettes had a final tip resistance of 1–2 MΩ when filled with internal recording solution. We carefully checked that the maximal voltage error due to residual series resistance after up to 95% compensation was always <5 mV.

**Voltage Clamp Protocols and Data Analysis**

The membrane was depolarized to various test potentials from a holding potential of −90 mV to record Ba²⁺ currents. The activation curve (conductance-voltage relationship) was derived from the current-voltage relationship obtained by plotting the peak current against various step depolarizations according to:

\[ g(V) = \frac{I}{V - V_{rev}} \]

with \( g \) being the conductance, \( I \) the recorded peak current at test potential \( V \), and \( V_{rev} \) the apparent observed Ba²⁺ reversal potential. Although the I-V relationship was not free of gating disturbances, we determined the apparent reversal potential by fitting the current-voltage relationship between −70 mV and 20 mV.

The following Boltzmann function was fit to the conductance-voltage relationship:

\[ g(V) = \frac{g_{max}}{1 + e^{-\frac{V - V_{1/2}}{k_V}}} \]

with \( g \) being the conductance at test potential \( V \), \( g_{max} \) the maximal conductance, \( V_{1/2} \) the voltage of half-maximal activation, and \( k_V \) a slope factor.

The residual current r400 was determined by dividing the peak Ba²⁺ current \( I_{peak} \) by each current trace by the mean residual current \( I_{res} \) during the last 10 ms of a 400 ms voltage pulse. Channels were not completely inactivated at this time point, so that this value served as a surrogate parameter of the time course of inactivation. For wild-type and domain II S4-S5 mutant channels coexpressed with β₁b, inactivation kinetics were quantified using monoexponential fits. To assess the time course of activation, a first-order exponential function was fitted to the current trace using ClampFit, yielding the activation time constant \( \tau_{act} \).

**Data and Statistical Analysis**

For variants in the domain II S6 segment, traces were displayed offline with pClamp 10.4 (Molecular Devices). Fits were performed using gnuplot 5.0 (Freedware, T. Williams & C. Kelley). Graphics were generated using a combination of Microsoft Excel (Microsoft Corporation) and Origin (version 2018; OriginLab) software, and statistics were performed using SigmaPlot 12.0 (Statcon). We recorded r400 values at different potentials but performed statistical testing only for a single potential i.e., 5 mV. For the voltage dependence of r400 and also for \( \tau_{act} \), we calculated the area under the curve as trapezoids using all data points between −17.5 mV and 42.5 mV. The resulting sum was used for statistical testing. All data were tested for normal distribution. For statistical evaluation, ANOVA on ranks (Kruskal-Wallis-Test) with Dunn’s posthoc test for not normally distributed data or one-way ANOVA (Bonferroni posthoc test) was used when datasets were normally distributed. All data are shown as means ± SEM. Boxes in boxplots indicate the interquartile range. Whiskers show the 5th and 95th percentiles.

For the domain II S4-S5 linker pIle603Leu variant, data were analyzed using the Clampfit 10.3 software (Molecular Devices) and fit using GraphPad Prism 6. Averaged data are plotted as mean ± SEM and statistical analysis was performed using Student’s t test or ANOVA, where \( p \leq 0.05 \) was considered significant.

**Results**

**Clinical Characteristics**

We identified 30 unrelated individuals with missense variants in CACNA1E (GenBank: NM_000721.3). A picture of a profound DEE emerged, with affected individuals typically having pharmaco-resistant seizures beginning in the first year of life, profound developmental impairment, hyperkinetic movement disorders, and severe axial hypotonia (Tables 1 and S1). Of the probands older than 2 years, 21/24 (88%) were non-verbal and non-ambulatory. Developmental regression occurred in 9/30 (30%) individuals, often in association with seizure onset. All affected individuals had prominent axial hypotonia, often with appendicular hypertonia; spastic quadriplegia was reported in 16/30 (53%) individuals. 13/30 (43%) affected individuals had congenital joint contractures ranging from isolated talipes equinovarus to arthrogryposis multiplex congenita, frequently prompting initial consideration of a congenital neuromuscular disorder.

Epilepsy was present in 26/30 (87%) individuals, with median age of seizure onset of 4.5 months (range 1 day to 47 months). Seizures began in the first year of life in 21/25 (84%) individuals for whom data were available. Epileptic spasms were the most common initial seizure type (14/26; 54%) followed by focal motor seizures (5/26; 19%). Most individuals (20/26; 77%) developed additional seizure types (Table S1); status epilepticus occurred in two individuals. Four individuals had no seizures identified (at age 1–4 years).
<table>
<thead>
<tr>
<th>Individual</th>
<th>Age (Sex)</th>
<th>Variant (NM_000721.3)</th>
<th>Seizure Types (Age of Onset of First Seizure)</th>
<th>EEG</th>
<th>MRI</th>
<th>Neurological Features</th>
<th>Development</th>
<th>Movement Disorder</th>
<th>Congenital Contractures</th>
<th>Macrocephaly</th>
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<tr>
<td>Individual 1</td>
<td>3y (M)</td>
<td>c.683T&gt;C (p.Leu228Pro) de novo</td>
<td>Myo (2w), FIAS</td>
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<td>white matter volume loss</td>
<td>spastic quadriplegia, hypotonia</td>
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<td>Individual 2</td>
<td>2y (F)</td>
<td>c.1042G&gt;C (p.Gly348Arg) de novo</td>
<td>ES (7 m), FIAS, GTCS, Myo</td>
<td>hypers, multifocal discharges</td>
<td>normal</td>
<td>severe truncal hypotonia, appendicular hypertonia</td>
<td>profound DD: NV, NA</td>
<td>dystonia</td>
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<td>25y (F)*</td>
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<td>multifocal discharges</td>
<td>normal</td>
<td>spastic quadriplegia, hypotonia</td>
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<td>dystonia</td>
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<td>+</td>
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<td>T (3y), GTCS</td>
<td>multifocal discharges</td>
<td>normal</td>
<td>spastic dystonic quadriplegia, hypotonia</td>
<td>profound DD: NV, NA</td>
<td>dystonia</td>
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<td>slow spike-wave</td>
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<td>profound DD: NV, NA</td>
<td>dystonia</td>
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<td>Individual 6</td>
<td>2y (M)*</td>
<td>c.1054G&gt;A (p.Gly352Arg) de novo</td>
<td>FM (2 m), ES</td>
<td>multifocal discharges</td>
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<td>severe axial hypotonia, appendicular hypertonia</td>
<td>profound DD: NV, NA</td>
<td>dystonia</td>
<td>–</td>
<td>–</td>
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<td>multifocal discharges</td>
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<td>spastic dystonic quadriplegia</td>
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<td>dystonia</td>
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<td>FM (14 m), T (14 m)</td>
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<td>dystonia</td>
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<td>dystonia, hyperkinetic</td>
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<th>Macrocephaly</th>
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<td>Myo (1d)</td>
<td>burst-suppression</td>
<td>normal</td>
<td>axial hypotonia</td>
<td>profound DD</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

(Continued on next page)
Hyperkinetic movement disorders were prominent, including severe dystonia in 12/30 (40%) and other dyskinetic disorders in 6/30 (20%) individuals; movement disorders were constant and profoundly disabling in some individuals. For example, in individual 2, dystonic movements were thought to have begun in utero and occurred every 2–3 min by 6 months of age and were not relieved by baclofen or benztropine (Videos S1 and S2).

Macrocephaly without other structural abnormalities on brain magnetic resonance imaging was present in 12/28 (43%) individuals for whom data were available. Common dysmorphic features were not observed. Out of 30 individuals, 7 (23%) had died with a median age of death of 2.7 years (range 11 months to 25 years). Reported causes of death were cardiorespiratory failure and status epilepticus.

Seizure Response to Topiramate

Although seizures were resistant to multiple anti-epileptic drugs (AEDs) in most individuals for whom data were available (20/25; 80%), five individuals (1, 15, 16, 21, 27) reported significant improvement in seizure control with topiramate, the only AED noted to have a substantial effect on seizure control in any participants (Table S1). Two individuals (16 and 27) remain seizure free for 2 and 5 years, respectively. However, individual 1 died following an episode of status epilepticus. Individual 21 reported substantial reduction in seizure frequency with topiramate but was discontinued due to increased sedation. Topiramate had no effect on seizure control in 10/18 (56%) individuals who were prescribed it; 3/18 (17%) individuals who were prescribed topiramate reported a reduction in seizures but were never seizure-free.

Genetic Analysis

Molecular genetic testing identified 14 missense variants in CACNA1E (GenBank: NM_000721.3) in 30 unrelated individuals (Table 1). For 29/30 individuals for whom DNA samples were available for both parents, de novo status of the variants and parentage were confirmed. Three recurrent variants—c.1054G>A (p.Gly352Arg) (n = 9), c.2104G>A (p.Ala702Thr) (n = 6), and c.2101A>G (p.Ile701Val) (n = 3)—accounted for 60% of individuals (18/30). One additional variant, c.4274C>A (p.Thr1425Asn), was identified in two individuals. Prominent clustering of CACNA1E variants (11/14; 79%) was noted in the cytoplasmic parts of all four S6 segments (Figure 1), which are presumed to form a crucial part of the activation gate in voltage-activated cation channels.

Loss-of-Function Variants

In addition to the 30 individuals with missense variants, we identified three further individuals with CACNA1E variants that introduce premature termination codons predicted to result in haploinsufficiency, with no other genetic abnormalities identified. Early death occurred in all three individuals: Individual 1 died following an episode of status epilepticus at 18 months of age; Individual 2 died of cardiorespiratory failure at 6 months of age; Individual 3 died at 3 months of age. These cases are consistent with previously reported cases of CACNA1E-related disorders, including severe dystonia in 12/30 (40%) and other dyskinetic movement disorders. For example, in individual 2, dystonic movements were pronounced in utero; movement disorders were constant and profoundly disabling in some individuals. For example, in individual 2, dystonic movements were thought to have begun in utero and occurred every 2–3 min by 6 months of age and were not relieved by baclofen or benztropine (Videos S1 and S2).

Table 1. Continued

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (Sex)</th>
<th>Variant (NM_000721.3)</th>
<th>Seizure Types (Age of Onset of First Seizure)</th>
<th>EEG</th>
<th>MRI</th>
<th>Neurological Features</th>
<th>Development</th>
<th>Movement Disorder</th>
<th>Congenital Contractures</th>
<th>Macrocephaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual 27</td>
<td>6y (f)</td>
<td>c.4274C&gt;A (p.Thr1425Asn) –</td>
<td>ES (5 m)</td>
<td>multifocal discharges</td>
<td>normal</td>
<td>mild hypotonia</td>
<td>severe DD: single words, walks with assistance</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Individual 28</td>
<td>4y (f)</td>
<td>c.4274C&gt;A (p.Thr1425Asn) –</td>
<td>–</td>
<td>not done</td>
<td>normal</td>
<td>hypotonia</td>
<td>severe DD: single words, ambulant</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Individual 29</td>
<td>4y (M)</td>
<td>c.4274C&gt;A (p.Thr1425Asn) –</td>
<td>–</td>
<td>not done</td>
<td>delayed myelination</td>
<td>profound appendicular hypotonia</td>
<td>severe DD: single words, ambulant</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Individual 30</td>
<td>2y (f)</td>
<td>c.5159C&gt;G (p.Ala1720Gly) –</td>
<td>ES (3w), Myo, GTCS, At, SE</td>
<td>multifocal discharges</td>
<td>thin corpus callosum</td>
<td>severe axial hypotonia, appendicular hypotonia</td>
<td>profound DD: NV, NA</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

Abbreviations: At, atonic seizures; CSWS, continuous spike and wave in slow wave sleep; d, days; DD, developmental delay; ES, epileptic spasms; F, female; FIAS, focal impaired awareness seizures; FM, focal motor seizures; gel, gelastic seizures; GTCS, generalized tonic-clonic seizures; hyps, hypsarrhythmia; ID, intellectual disability; m, months; M, male; Myo, myoclonic seizures; NV, non-verbal; NA, non-ambulatory; SE, status epilepticus; T, tonic seizures; w, weeks; y, years. Further clinical details are provided in Table S1.

a Deceased, age at death.
known causative genetic variants identified (individuals 31–33; Table S2). Individual 31 has a mosaic nonsense variant with a mutant allele fraction of 27% (6/22 reads) in peripheral blood leukocytes. In individual 32, a CACNA1E frameshift variant was inherited from an apparently unaffected father. Parental DNA samples were unavailable for individual 33, who has a heterozygous germline nonsense variant. All three individuals had comparably milder phenotypes, achieving independent ambulation at 15–18 months and acquiring single words; 2/3 individuals had epilepsy.

Genotype-Phenotype Correlations

Some genotype-phenotype correlations emerged in our cohort of individuals with CACNA1E-encephalopathy. Dystonia was a prominent feature in all nine individuals with the recurrent c.1054G>A (p.Gly352Arg) variant. This variant is in close proximity to the c.1042G>C (p.Gly348Arg) variant in individual 2 who also demonstrated profound dystonia. Dystonia was less common in individuals with other variants, only observed in 2/19 (11%) remaining probands, suggesting that variants in the domain I GX3G motif may predispose to prominent hyperkinetic movement disorders. Two individuals harboring the c.4274C>A (p.Thr1425Asn) variant and one individual with the c.4288G>A (p.Gly1430Arg) variant presented with a comparatively milder clinical picture. All three probands were the only individuals in the cohort to speak single words and walk independently or with assistance, in contrast to the profound impairment in the remainder of the cohort. Two of these probands had not developed seizures by age 4 years, and the other had been seizure free for 5 years and off AEDs at age 6 years.

The six individuals harboring the recurrent c.2104G>A (p.Ala702Thr) variant had a relatively homogeneous phenotype that was representative of the overall CACNA1E-encephalopathy phenotype. All individuals had refractory infantile-onset epilepsy, epileptic spasms, severe hypotonia, and profound developmental impairment. Five out of six individuals (83%) harboring the c.2104G>A (p.Ala702Thr) variant had congenital joint contractures and macrocephaly; hypsarrhythmia on EEG consistent with a diagnosis of West syndrome was observed in four of these individuals (67%). Two of these six individuals died in early childhood at ages 1 and 3 years.

Functional Analysis

Domain II S6 Variants

We evaluated the functional effects of three missense variants (p.Phe698Ser, p.Ile701Val, and p.Ala702Thr) located in the cytoplasmic end of the S6 segment of domain II (IIS6; Figure 1). For the IIS6 variants, we performed electrophysiological recordings of tsA201 cells that were transiently transfected with either wild-type or mutant a1E-subunits together with the b2d-subunit, confirmed by the green fluorescence of EGFP which was co-expressed via an internal ribosome entry site (IRES). All three IIS6 variants exhibited consistent abnormalities of activation and inactivation kinetics compared to wild-type channels (Figure 2; Table 2). The activation curve was shifted by approximately −10 mV for all three variants (Figure 2), while the time course of activation was not altered. Additionally, the time course of fast inactivation was significantly slowed, as indicated by an increased residual current after a 400-ms depolarizing pulse normalized to the peak current (r400) (Figures 2 and S1; Table 2).

Domain II S4-S5 Linker Variant

The p.Ile603Leu variant, located in the domain II S4-S5 linker (IIS4-S5; Figure 1), was co-expressed with b1b and a2d subunits in tsA201 cells and compared functionally to the wild-type channel. This variant resulted in a massive increase in whole-cell current density (Figures 3 and S2) to a level that in many cases precluded functional biophysical characterization. In a subset of cells where the current could be properly clamped, our analysis revealed a >10 mV hyperpolarizing shift in half activation voltage (Figures 3 and S2).
and S2; Table 2). There was no significant effect on channel inactivation.

Discussion

Here we describe CACNA1E-encephalopathy as a disorder of neuronal calcium channel dysfunction in 30 individuals with disease-causing missense CACNA1E variants. All identified individuals with CACNA1E-encephalopathy present with similar clinical features, including profound developmental impairment, infantile-onset refractory epilepsy, and severe axial hypotonia. Developmental and epileptic encephalopathies are genetically heterogeneous and can be caused by pathogenic variants in genes encoding other voltage-gated neuronal ion channels, including SCN2A, SCN8A, KCNQ2, and CACNA1A.33–39 Some aspects of CACNA1E-encephalopathy are clinically similar to other genetic DEEs, including early-onset refractory seizures, developmental impairment, and abnormalities in tone. However, notable features of CACNA1E-encephalopathy include prominent hyperkinetic movement disorders, congenital joint contractures, macrocephaly, and early death in a subset of affected individuals.

Functional analysis of several missense variants revealed highly consistent gain-of-function effects, characterized by facilitated voltage-dependent activation, slowed inactivation, and increased current density. Voltage-dependent calcium channel α1-subunits are responsible for the electrophysiological properties of the channel and are comprised of four homologous domains (I to IV), with each domain containing six transmembrane segments (S1 to S6). The four S6 transmembrane helices line the channel pore,33 and the structure at the cytoplasmic end of S6 segments contains the presumed activation gate and is crucial in channel gating.33,34 Disease-causing missense variants in our cohort clustered in cytoplasmic parts of all four S6 transmembrane segments, suggesting that the observed gain-of-function effects perturb the gating properties of the CaV2.3 channel.

Prior to our discovery of pathogenic variants in CACNA1E as a cause of human disease, selected variants had already been artificially introduced into different S6 segments in biophysical and electrophysiological studies to characterize the structure and function of CaV2.3 channels, and our functional analysis revealed results consistent with previous studies (Figure S3).33,34 We now identify three previously studied variants in CaV2.3 (p.Gly352Arg, p.Ile701Val, p.Ala1720Gly) as disease causing in our cohort. Most of the previously investigated variants (including p.Gly352Arg, p.Ile701Val/Gly, and p.Ala1720Gly) also shifted the voltage dependence of activation toward more negative potentials and slowed

Figure 2. Functional Effects of CACNA1E (GenBank: NM_001205293.1) Domain II S6 Variants Introduced into α1E,1 and Co-expressed with β2d in tsA-201 Cells using 15 mM Ba2+ as Charge Carrier
(A) Current traces elicited by depolarizing voltage pulses in 7.5-mV steps from a holding potential of −90 mV.
(B) The voltage dependence of activation was similarly and highly significantly shifted for all three variants.
(C) The residual current (I400) at +5 mV was determined by dividing the mean current of the last 10 ms of a 400-ms test pulse (Ires) by the peak current (IPeak) of the same pulse. Numbers in parentheses denote the number of experimental readings per variant. Data are represented as means ± SEM (and in addition all measured values in C). *p < 0.05; **p < 0.01; ***p < 0.001.
the inactivation time course.33,34 The p.Gly348Arg and the recurrent p.Gly352Arg variants are part of a highly conserved GXG motif that is located in the cytoplasmic end of the domain I S6 segment and plays an essential role in voltage-dependent inactivation of voltage-gated calcium channels. Notably, Gly348 and Gly352 in CaV2.3 are paralogous to Gly402 and Gly406 in CaV1.2 encoded by CACNA1C which are altered (p.Gly402Ser, p.Gly406Arg) in Timothy syndrome, a severe developmental disorder with fatal cardiac arrhythmia and autism.6,7

Although most disease-causing variants cluster in S6 transmembrane segments, the identified p.Ile603Leu variant is located in the linker between segments S4 and S5 in domain II. Functional analysis also identified strong gain-of-function properties for this variant, revealing increased current density and facilitated activation. These observed gain-of-function effects are also consistent with prior CaV2.3 biophysical studies showing that the domain II S4-S5 linker region is important for regulating channel activation.40

In contrast to de novo missense variants with a gain-of-function effect, the role of CACNA1E haploinsufficiency is less clear. We identify three individuals with loss-of-function CACNA1E variants with comparably milder phenotypes. In one case the frameshift variant was transmitted from an unaffected parent. Several loss-of-function variants are reported in the gnomAD database, but loss-of-function variants do not appear to be well tolerated in healthy individuals (pLI = 1.0).32

The AEDs topiramate and lamotrigine target CaV2.3 channels and reduce R-type calcium currents.41,42 Five individuals with CACNA1E-encephalopathy achieved seizure freedom on topiramate therapy, which was the only AED to meaningfully impact seizure control among any affected individuals. These data indicate that topiramate, an R-type channel blocker, has a positive effect in some individuals, possibly because its inhibitory mechanism targets the gain-of-function pathophysiology we have demonstrated in vitro. This is in stark contrast to a large number of other AEDs that did not show a sustained beneficial effect in more than a single individual.

In summary, we identified a genetic DEE associated with de novo missense variants in CACNA1E in 30 individuals, with notable features of congenital contractures and macrocephaly in many individuals. Profound impairment with hypotonia and movement disorders were often part of the CACNA1E-encephalopathy phenotype. Functional analysis revealed dramatic gain-of-function effects, indicating increased calcium inward currents that may affect neuronal excitability and synaptic transmission. The identification of pathogenic gain-of-function variants in CACNA1E in these individuals adds to the growing list of channelopathies causing neurodevelopmental disorders and DEEs. We implicate facilitated R-type calcium currents as a disease mechanism in human epilepsy, which provides a promising target for the development of precision medicines for this devastating disease.

Accession Numbers
The accession number for the CaV2.3 α1E-3 construct used in this paper is GenBank: L29385.1

Supplemental Data
Supplemental Data include Supplemental Methods, three figures, two tables, and two videos and can be found with this article online at https://doi.org/10.1016/j.ajhg.2018.09.006.
Consortia

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Declaration of Interests

I.E.S. has received support from and/or has served as a paid consultant for UCB, Eisai, Athena Diagnostics, GlaxoSmithKline, Biocodex, Biomarin, and Nutricia and may accrue future revenue on pending patent WO61/010176 (filed: 2008): Therapeutic Compound. H.C.M. is a member of scientific advisory boards for Lennox Gastaut Syndrome Foundation, Dravet Syndrome Foundation, and SPARK. The remaining authors declare no competing interests.

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Figure 3. Functional Effects of the CACNA1E (GenBank: NM_001205293.1) Domain II S4-S5 Variant p.Ile603Leu Introduced into δ1E.3 and Co-expressed with β1b and α2δ1 in tsA-201 Cells
(A) Current traces elicited by depolarizing voltage pulses in 5 mV steps from a holding potential of −100 mV as recorded with 2 mM Ca2+ as charge carrier.
(B) Voltage dependence of activation recorded in 2 mM Ca2+ revealing a significant difference between WT and mutant channels. Numbers in parentheses denote the number of experimental readings per variant.
(C) Mean peak current densities for WT and p.Ile603Leu channels recorded in 2 mM Ca2+ or 5 mM Ba2+. Data are represented as mean ± SEM. Numbers in parentheses denote the number of experimental readings per variant. Asterisks denote statistical significance (Student’s t test, *p ≤ 0.05, **p ≤ 0.01, and ****p ≤ 0.0001).
References


