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Journal:	*Brain*
Manuscript ID	BRAIN-2022-00332.R2
Manuscript Type:	Original Article
Date Submitted by the Author:	29-Jul-2022

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Methodology:	GENETICS, GENOMICS & EPIGENETICS
Subject area:	EPILEPSY

Heterozygous *ATP6V0C* Variants Cause a Neurodevelopmental Disorder Associated with Epilepsy and Impair Vacuolar H^+-ATPase Function

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Abstract

The vacuolar H^+-ATPase (V-ATPase) is an enzymatic complex that functions in an ATP-dependent manner to pump protons across membranes and acidify organelles, thereby creating the proton/pH gradient required for membrane trafficking by several different types of transporters. We describe heterozygous point variants in *ATP6V0C*, encoding the c-subunit in the membrane bound integral domain of the V-ATPase, in 27 patients with neurodevelopmental abnormalities with or without epilepsy. Corpus callosum hypoplasia and cardiac abnormalities were also present in some patients. *In silico* modeling suggested that the patient variants interfere with the interactions between the ATP6V0C and ATP6V0A subunits during ATP hydrolysis. Consistent with decreased V-ATPase activity, functional analyses conducted in *Saccharomyces cerevisiae* revealed reduced LysoSensor fluorescence and reduced growth in media containing varying concentrations of $CaCl_2$. Knockdown of ATP6V0C in Drosophila resulted in increased duration of seizure-like behavior, and the expression of selected patient variants in *Caenorhabditis elegans* led to reduced growth, motor dysfunction, and reduced lifespan. In summary, this study establishes *ATP6V0C* as an important disease gene, describes the clinical features of the associated neurodevelopmental disorder, and provides insight into disease mechanisms.

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Running title: Heterozygous *ATP6V0C* Variants Cause

Keywords: V-ATPase; ATP6V0C; VMA3; epilepsy genetics; neurodevelopmental disorders

Abbreviations: eAUC = empirical area under the curve; gnomAD = genome aggregation database; NMD = nonsense mediated decay; SV = synaptic vesicle

Introduction

The vacuolar H^+-ATPase (V-ATPase) is a highly conserved enzymatic complex that functions in an ATP-dependent manner to pump protons across membranes and acidify organelles. The V-ATPase is comprised of a peripheral V_1 domain and an integral V_0 domain (**Fig. 1**). The V_1 domain is responsible for the hydrolysis of ATP creating the necessary energy to translocate protons through the V_0 domain via a rotational mechanism.[1] The V-ATPase plays a crucial role in many cellular processes involving membrane trafficking by creating a proton/pH gradient used by several different types of transporters.[1,2]

The human V-ATPase, comprised of 13 different subunits, is encoded by 23 genes (**Supplementary Table 1**). This genetic redundancy allows for the formation of tissue-specific V-ATPase complexes, including in synaptic vesicles (SVs) where it creates the necessary proton/pH gradient to load various neurotransmitters.[1,2] To date, twelve genes corresponding to eight different subunits of the V-ATPase have been associated with human disease (**Supplementary Table 1**).[3-13] Early-onset epilepsy has been observed in patients with variants in either *ATP6V1A* or *ATP6V0A1*, with heterozygous, *de novo* variants leading to less severe presentations when compared to patients with biallelic variants.[14-16] Pathogenic variants in *ATP6V1B2* can cause epileptic conditions such as Zimmerman-Laband (MIM#616455) and DOORS syndromes, or deafness and nail dysplasia without epilepsy (DDOD, MIM#124480).[11,12,17,18] An accessory protein to the V-ATPase, encoded by *ATP6AP2*, is associated with X-linked syndromic intellectual disability that can present with or without epilepsy (MIM#300423).[19,20]

ATP6V0C, a three-exon gene (**Fig. 2A**) located on human chromosome 16p13.3, encodes the 155 amino acid c-subunit of the V_0 domain which along with the c″ subunit (encoded by *ATP6V0B*) forms the intramembrane c-ring that facilitates the movement of

protons across the membrane (**Fig. 1**).[21] The process of proton translocation is reliant on a glutamate residue at position 139 (p.E139) in ATP6V0C as well as an arginine residue (p.R735) in ATP6V0A.[1]

We previously described patients with developmental delay, intellectual disability, microcephaly, and seizures with 16p13.3 microdeletions encompassing a minimal overlapping region that included *TBC1D24, ATP6V0C,* and *PDPK1*.[22] By reviewing the known function(s) and expression patterns of genes in the minimal overlapping region, we proposed haploinsufficiency of *ATP6V0C* as the primary contributor to the clinical features of 16p13.3 microdeletion syndrome.[23] However, we did not provide any functional evidence to support our claim.

Most recently, Ittiwut *et al.*[24] reported a *de novo* stop-loss variant in *ATP6V0C* in an individual with epilepsy and intellectual disability. Analysis of RNA derived from the patient's leukocytes revealed that, as expected, the mutant transcript escaped nonsense mediated decay (NMD). The authors proposed haploinsufficiency as the likely pathomechanism given the observed decrease in mRNA levels; however, a dominant negative effect is also possible given the transcript escape from NMD. Hence, thus far it is unknown if *ATP6V0C* missense variants are a cause of human disease, and the mechanistic basis of *ATP6V0C*-associated human disease is unclear.

In this study, we report the identification of heterozygous *ATP6V0C* missense variants in 27 patients with a novel syndrome of developmental delay, epilepsy, and intellectual disability. We present multiple lines of computational and functional analyses to demonstrate that these variants are pathogenic and disrupt V-ATPase activity.

Materials and methods

Identification of Individuals with *ATP6V0C* Variants

Authorization was obtained at each site to release deidentified patient medical information to study investigators and when applicable informed consent was obtained through protocols approved by the institutional review boards at each site of patient recruitment. Patients with *ATP6V0C* variants were identified via GeneMatcher, and by interrogating the 100,000 Genomes database, the Deciphering Developmental Disorders (DDD) study, and ClinVar.[25-27] We also screened whole-exome sequencing (WES) data from epilepsy patients referred for genetic testing at EGL Genetics. Three patients (Patients 2, 13 and 27) were previously reported in other publications.[24,25,28] For Patients 2 and 27, clinical information was obtained from the previous publications, whereas the referring clinician provided clinical information for Patient 13. Patient 5 was reported in ClinVar and clinical information was provided by the depositing organization (**Supplementary Table 2**). Clinical information for all other patients was collected using a custom form provided to each site.

Sequencing and Analysis of Sequence Data

Whole-exome or whole-genome sequencing was performed on patient DNA extracted through standard protocols. All libraries were sequenced on Illumina HiSeq systems. Sequence alignment and variant calling were performed at each site and further details are provided in **Supplementary Table 2**. When possible, *ATP6V0C* variant segregation was confirmed with Sanger sequencing using standard protocols.

Lollipop and Missense Tolerance Ratio Diagram

The Lollipop diagram was created as previously described using the UniProt accession number, P27449.[29,30] Non-synonymous and synonymous population variants were downloaded from

gnomAD (v.2.1.1).[31] Resulting diagrams of gnomAD and patient variants were merged into a single image for ease of visualization, and the locations of the transmembrane domains were superimposed over the resulting image. A missense tolerance ratio (MTR) plot was generated using MTR-Viewer v2, with a codon window size of 21, on the ENST00000330398 transcript.[32]

Drosophila Studies

The Drosophila ortholog, Dmel\Vha16-3 (CG32090), was knocked-down using pan-neuronal (elaV-GAL4) expression of a gene-specific RNAi construct (VDRC-102067), provided by the Vienna Drosophila Resource Center. As a control, an RNAi to GFP was used. Seizure-like behavior was elicited using electroshock of wall-climbing third instar larvae as described in Marley and Baines 2011.[33] Drugs, solubilized in DMSO, were fed to larvae by mixing (at 2mM) in molten fly food which was then allowed to cool and set before being seeded with first instar larvae.

In silico Variant Modeling

Patient and gnomAD variants were displayed in the context of a structure for the V_0 domain of human V-ATPase (PDB: 6wlw).[21,34] PyMOL and Swiss PDB Viewer were used for visualization of protein structure.[35]

Saccharomyces cerevisiae Strains and Plasmids

E. coli and yeast manipulations were performed following standard molecular biology protocols.[36] The *vma3::kanMX* yeast strain (*vma3Δ,* Cat No. YSC6273-201929081) was obtained from GE Dharmacon and is isogenic with BY4741 (*MATa his3Δ leu2Δ met15Δ ura3Δ*). Plasmids are listed in **Supplementary Table 3**. A plasmid (pKM16) containing the promoter and wild-type open reading frame for *VMA3* (the yeast ortholog of *ATP6V0C*) was

generated by amplifying a 924bp fragment from *S. cerevisiae* gDNA and cloning it into pRS316 using *BamHI* and *SacI* (Forward cloning primer: 5' taagcaggatccagcaatgaaataggccgtctac, Reverse cloning primer: 5' taagcagagctccttgaaatgaggtagtttgg) .[37] pKM16 was used as the backbone to generate all variants via conventional cloning techniques or the QuikChange XL Site-Directed Mutagenesis Kit (Agilent Technologies). Sanger sequencing was performed to confirm the presence of each variant as well as the absence of unwanted substitutions.

Plasmids were transformed into the *vma3Δ* strain and selected on plates containing synthetic minimal media plus dextrose supplemented to select for a *URA3* plasmid (SD-ura). Selected transformants were maintained on SD-ura throughout the course of experiments.

Serial Dilution Spotting Assay

Liquid cultures of transformants were grown at 30°C overnight in SD-ura adjusted to a pH of 5.5. 1 OD_{600} per ml of cells was collect and suspended in dH_20. Serial 10-fold dilutions were spotted onto SD-ura plates. Plates were imaged after incubation at 30°C for 48 hours.

LysoSensor Uptake and Confocal Imaging

Cells were collected at OD_{600} 0.6-1.0 and incubated with LysoSensor Green DND-189 (Invitrogen, Cat# L7535) as previously described.[38] Cells were resuspended in 1X PBS (pH 7.6) to an OD_{600} of 0.6, deposited on 1.5% agarose pads, and visualized immediately. Images were taken at room temperature using a confocal laser scanning microscope (A1R HD25, Nikon) with an Apo TIRF 60x 1.49 NA oil immersion lens, WD 0.12mm (Nikon). Images were acquired using NIS-Elements (AR 5.21.02, Nikon) and processed using FIJI. All cells visible in the DIC channel were selected, the selection was copied to the FITC channel, and the mean grey area was calculated for each cell. Measurements were corrected for background signal by

subtracting the mean grey area of a background only selection from each image. Two biological replicates, in separate experiments, totaling 71-132 cells for each variant were analyzed.

Generation of Growth Curves

Liquid cultures of transformants were grown at 30°C overnight in SD-ura adjusted to a pH of 5.5. Overnight cultures were diluted 1:20 in dH_20 and further diluted 1:10 in YPD, pH 5.5, with 5mM, 100mM or 200mM $CaCl_2$. OD_{600} measurements were taken every 15 minutes for 30 hours at 30°C with shaking using an ELx808 plate reader (BioTek). Three independent transformants were assayed in triplicate for each variant. The R package, GrowthCurver, was used to calculate the empirical area under the curve (eAUC) for each replicate.[39]

Caenorhabditis elegans Studies

All *C. elegans* strains were cultured and handled as per standard methods. All experiments were carried out at 20°C. Mutations were knocked-in via CRISPR/Cas9, and homozygous worms were studied. Strains used in this project are described in **Supplementary Table 4**.

Paralysis Assays

In three separate experiments, 30-40 L4 worms (in triplicate) were picked to standard NGM plates either with 51mM NaCl (physiological conditions), or with 200mM or 300mM NaCl, and scored daily for paralysis starting the day after they were picked. A total of 270-360 worms were tested per condition. Worms were counted as paralyzed if they failed to move their body upon prodding with a platinum wire and were considered dead if they failed to move their head and showed no pharyngeal pumping when prodded. Dead or lost animals were censored from statistical analyses. Worms were transferred every 2 days to avoid progeny.

Lifespan Assays

Lifespan experiments were conducted similarly to paralysis assays. Two separate experiments were performed using 35-40 worms in triplicate, leading to a total 315-360 worms tested per condition. Worms were counted every second day from day 1 of adulthood until death. Lost animals were censored from statistical analyses, paralyzed worms were not censored and were kept until death.

Liquid Culture Motility Assays

Synchronized day 1 adult worms were transferred into 200uL of M9 buffer with or without 350mM NaCl in each well of a 96 well plate, to a density of 30 worms per well. Motility was automatically analyzed for 4 hours using a WMicrotracker-One plate reader (PhylumTech).

WormLab Analysis

Synchronized day 1 adult worms were video recorded for 30-33 seconds using a Leica Stereomicroscope S9i. Automated movement and worm size analyses were conducted using WormLab software (MBF Biosciences) which tracks individual worms from the recorded videos. Activity index is defined by the brush stroke (area "painted" by the animal's body in a single complete stroke) normalized by the time taken to perform two strokes. Wave initiation rate is defined as the number of body waves initiated from either the head or the tail per minute. Swimming speed was measured over a two-stroke interval.[40] For body size analysis, worms were recorded on bacteria free NGM plates. For swimming parameters, worms were placed in M9 with 500mM NaCl and recorded 30 minutes later. At least 50 worms were recorded in two independent experiments.

Aldicarb Sensitivity Assays

Worms were grown on standard NGM plates until day 1 of adulthood and then transferred to NGM plates containing 1mM aldicarb. Paralysis was assayed every 30 minutes for 2 hours. Animals were counted as paralyzed if they failed to move upon prodding with a platinum wire.

Statistical Analyses

Drosophila recovery time was analyzed using one-way ANOVA with Dunnett's post-hoc test for multiple comparisons. Recovery time after drug treatment was normalized to the vehicle only control. A Fisher's Exact test was used to demonstrate the presence of a variant hot-spot in the fourth transmembrane domain of ATP6V0C. For LysoSensor, fluorescence values for each cell measured were normalized to the mean fluorescence of the wild-type rescue. For the growth rate assay, eAUC values were normalized to the mean eAUC of the wild-type rescue within each plate. A one-sample t-test was used to compare the mean fluorescence and eAUC for each variant to a hypothetical mean of 100 (representing the wild-type rescue). Significance levels were corrected for multiple comparisons using a Bonferroni correction (LysoSensor and growth at 5mM, $\alpha = 0.0003125$; 100mM, $\alpha = 0.00714$; 200mM, $\alpha = 0.00833$). A two sample t-test (two-tailed) was used to compared p.G103S to p.F137L at 200mM. Paralysis curves and lifespan assays were compared using the log-rank (Mantel–Cox) test. The liquid culture motility assays (WormTracker) results were analyzed using two-way ANOVA to compare each variant to the wild-type N2 strain. WormLab results were analyzed using a one-way ANOVA with a Dunnett's post-hoc test for multiple comparisons to compare each variant to the wild-type N2 strain. The WormLab data is presented as box and whisker plots indicating minimal and maximal data points. Normalization and statistical analyses were carried out using Prism 9.0 (GraphPad Software Inc.). All data is presented as mean ± SEM and $\alpha = 0.05$ was used unless otherwise noted.

Data and Reagent Availability

All strains and plasmids (**Supplementary Tables 3 and 4)** used in this study are available upon request. The human datasets presented in this article are not publicly available due to ethical and privacy restrictions. Requests to access the human datasets should be directed to the corresponding authors.

Results

Identification of *ATP6V0C* Variants in Patients

We identified 27 patients with heterozygous *ATP6V0C* variants through GeneMatcher, 100,000 Genomes database, the DDD study, ClinVar, published literature, and EGL Genetics. Of the 27 patients, 22 had missense substitutions (18 variants were unique), 4 had frameshifting variants, and 1 had a stop-loss variant (**Table 1**). The variants p.A138P, p.A149T, and p.L150F were recurrent, each being seen in two or more unrelated individuals. Different substitutions at p.A95 and p.L150 were also observed. Patients 4, 9, 15 and 19 were each found to be mosaic for their identified *ATP6V0C* variant.

Multiple lines of evidence support the pathogenicity of the identified patient variants. Firstly, all patient variants were absent from the Genome Aggregation Database (gnomAD, v.2.1.1), which is compilation of exome and genome sequencing data from large-scale sequencing projects for which efforts have been made to remove individuals affected by severe pediatric disease. Secondly, in 24 patients where biologic parent DNA was available, the variants were found to have occurred *de novo*. Thirdly, all missense substitutions affected highly conserved residues (**Fig. 2B**), with 17 out of the 18 unique missense variants having CADD scores that placed them in the top 1% of predicted deleterious variants. Lastly,

ATP6V0C has a predicted intolerance to missense and loss of function variation with only 21 population missense variants observed in gnomAD compared to the expectation of 108 (observed/expected = 0.19) and 0 loss of function variants observed compared to the expectation of 4.5 (**Fig. 2C-D)**. In addition, all *ATP6V0C* gnomAD variants are observed at low frequencies (three times or less).[41] Taken together, when the ACMG/AMP variant classification guidelines are applied, all *ATP6V0C* variants identified in the patients are predicted to be likely pathogenic or pathogenic (**Supplementary Table 2**).[42]

ATP6V0C Variants Cause a Human Syndrome of Developmental Delay, Epilepsy, and Intellectual Disability

The primary clinical presentation of the identified patients was developmental delay with early-onset epilepsy and intellectual disability **(Table 1**). The mean age of seizure onset was 24.6 ± 8.0 months, with 14 of 18 patients for whom this information was available having onset prior to 24 months. Based on clinical information from 19 patients, the most common seizure types observed were generalized tonic-clonic (12/19), focal (7/19), atonic (6/19), and myoclonic (5/19). Intellectual disability, ranging from mild to severe, was seen in 16/16 patients who were old enough for a formal diagnosis and for whom this information was available. Development delay was seen in 21/23 patients. Twenty-one patients had MRIs with thirteen showing abnormalities (**Supplementary Table 2**). Common findings in MRIs included agenesis/hypoplasia of the corpus callosum (**Supplementary Fig. 2**) or cerebellar vermis (Patients 5, 6, 18, 20 and 26), and delayed myelination (Patients 6, 18, 22 and 24). Four patients were reported to have cardiac abnormalities: Patient 3 had pulmonary valve stenosis, Patient 6 had a thickened left ventricular wall, Patient 7 had a heart murmur, and Patient 13 exhibited several cardiac defects including hypertrophic cardiomyopathy, mitral valve prolapse, and mild to moderate mitral valve regurgitation. Patients 5 and 24 showed dental enamel defects, with

Patient 24 lacking dental enamel. It should be noted that Patient 7 also has a *de novo* 2.3Mb deletion in 20q11.22-11.23 which has been associated with developmental delay and dysmorphism, and Patient 13 has biallelic variants in *LZTR1* which has been associated with Noonan-like syndrome (MIM#605375).[43]

Collectively, these data show that *ATP6V0C* variants cause a human syndrome of developmental delay, intellectual disability, and epilepsy. Furthermore, as most individuals were ascertained on the basis of genotype (i.e., having a variant in *ATP6V0C*), their phenotypic convergence on reverse phenotyping further supports the pathogenicity of the variants described in this study.[44]

ATP6V0C Knockdown in Drosophila Results in Seizure-like Behavior

Based on our hypothesis that haploinsufficiency of *ATP6V0C* drives the neurological phenotype of 16p13.3 microdeletion syndrome and the identification of patients with frameshift variants, we first tested the consequences of ATP6V0C knockdown in Drosophila.[23] The orthologous protein in Drosophila, Dmel\Vha16-3, (CG32090), shows 78% amino acid identity to ATP6V0C. CG32090 was knocked-down via pan-neuronal expression of a gene-specific RNAi construct (VDRC-102067). The same pan-neuronal driver line (elaV-GAL4) driving expression of GFP RNAi (elaV>GFP RNAi), and the homozygous 102067 RNAi line without the elaV-GAL4 driver (102067 RNAi) were used as controls. Following knock-down of CG32090 (elaV>102067 RNAi), wall climbing third instar larvae showed a significant increase in recovery time (i.e., longer seizure-like behavior) after electroshock ($p < 0.0001$, one-way ANOVA, **Fig. 3A**). Pre-treatment of these larvae with a variety of established antiepileptic drugs resulted in significant reductions in recovery time with levetiracetam and topiramate ($p < 0.001$), and to a lesser extent with lamotrigine and valproate ($p < 0.01$ and <

0.05, respectively, **Fig. 3B**). Phenytoin, at the same concentration (2mM in fly food) did not significantly alter recovery time. These results are consistent with the hypothesis that haploinsufficiency of *ATP6V0C* contributes to seizures.

ATP6V0C Variants Are Predicted to Interfere with V-ATPase Rotary Mechanism

Higher conservation across ATP6V0C orthologs was seen at sites of patient variants compared to gnomAD variants (**Supplementary Fig. 1**). To understand the basis of pathogenicity of the *ATP6V0C* patient missense variants, we first turned to *in silico* modelling. Upon hydrolysis of ATP, the c-ring (comprised of nine copies of ATP6V0C and one copy of ATP6V0B) rotates within the membrane delivering protons to the ATP6V0A subunit (encoded by *ATP6V0A*) for transport across the membrane (**Fig. 1**).[21] Transmembrane (TM) domains 2 and 4 of ATP6V0C are outward facing and interact with ATP6V0A during this rotational mechanism.[45,46] The location of patient variants shows an enrichment within TM domains and the presence of a 'hot-spot' in the fourth TM of ATP6V0C ($p = 0.006$, Fisher's Exact test, **Fig. 2C**). When viewed structurally, some patient and gnomAD variants are located at sites of packing between c-ring subunits; however, many more patient variants are located outward-facing from the c-ring so as to potentially interfere with interactions between mutant ATP6V0C subunits and the ATP6V0A subunit (**Fig. 4A-B**). These data raise the possibility that outward facing *ATP6V0C* missense variants may have a dominant negative effect.

ATP6V0C Patient Variants Are Deleterious in Yeast

Budding yeast, *S. cerevisiae,* possesses an *ATP6V0C* ortholog, *VMA3,* which shares 72% amino acid identity and a conserved four transmembrane protein structure. *S. cerevisiae* has been previously used to study the functional effects of variants in other V-ATPase subunits.[8,47-50]

Given that all identified patient missense variants affected residues that are conserved between human and yeast, we expressed 12 of the patient variants in *VMA3* using a centromeric plasmid in a *vma3Δ* yeast strain (**Supplementary Fig. 1, Supplementary Table 3**). Six additional variants were identified after completion of these experiments and, therefore, were not modeled in yeast.

We also examined the functional effects of three population variants in *ATP6V0C* from gnomAD (p.R48W, p.G103S, p.M131I; **Supplementary Fig. 1, Supplementary Table 5**) on V-ATPase function. p.R48W was chosen as it effects the same residue as the p.R48P patient variant. p.G103S and p.M131I were chosen as they have the highest CADD scores for variants seen twice and once, respectively, in gnomAD. The altered residues are also conserved between human and yeast (**Supplementary Fig. 1**). All *ATP6V0C* variants in gnomAD (21 total) are rare (**Supplementary Fig. 1**), being seen no more than three times out of approximately 250,000 alleles. In addition, we also generated and tested p.E139A, which removes the glutamate residue necessary for V-ATPase function.[1]

To first establish the ability of the *vma3Δ* strain to grow when transformed with plasmids containing patient or population variants, a serial dilution spot assay was performed on SD-ura plates. We confirmed the ability of all transformants to grow under no selective V-ATPase pressure, thereby allowing us to examine V-ATPase function in our yeast model (**Supplementary Fig. 3**).

LysoSensor Green DND-189 (pK_a ~ 5.2) is an acidotropic dye that accumulates in the membranes of vacuoles. Upon protonation, quenching of the fluorescent probe is relieved and fluorescent intensity increases in a pH dependent manner. It has been previously demonstrated that V-ATPase activity in yeast and fluorescent intensity of LysoSensor Green are correlated.[38] We looked for rescue of V-ATPase function by transformation of each patient or population

variant into the *vma3Δ* strain. Nine patient variants and p.E139A resulted in little to no fluorescence (**Fig. 5A, Supplementary Fig. 4**). Two patient variants (p.G63A and p.L150F) and two gnomAD variants (p.R48W and p.G103S) showed intermediate levels of fluorescence intensity compared to the wild-type rescue. One gnomAD variant (p.M131I) and one patient variant (p.F137L) show levels of fluorescence intensity that were comparable to wild-type rescue. Overall, 11 of 12 patient variants and all gnomAD variants elicited significant decreases in fluorescence intensity when compared to the wild-type rescue ($p < 0.01$, one sample t-test, **Fig. 5A**).

V-ATPase, and therefore ATP6V0C, function is required for yeast to grow at increased $CaCl_2$ concentrations.[47,51] To further examine the consequences of patient *ATP6V0C* variants on V-ATPase function, transformants were used to inoculate YPD with 5mM $CaCl_2$ and growth curves were generated for each variant (**Fig. 5B-E**). Eight patient variants and p.E139A showed negligible growth at 5mM $CaCl_2$. The remaining four patient variants and all gnomAD variants showed varying degrees of growth at 5mM $CaCl_2$. Overall, significantly less growth compared to wild-type rescue was seen for 11 of 12 patient and the three gnomAD variants tested ($p < 0.0001$, one sample t-test, **Fig. 5F**). The results seen at 5mM $CaCl_2$ mirrored those seen with LysoSensor uptake ($r^2 = 0.7921$, **Supplementary Fig. 5**).

Next, patient variants that grew at 5mM $CaCl_2$ along with the three gnomAD variants were tested at 100mM and 200mM $CaCl_2$ to determine whether a higher concentration of calcium would provide further separation of variants relative to the wild-type rescue. At 100mM $CaCl_2$, p.L150F showed almost no growth compared to wild type ($p < 0.0001$, one sample t-test, **Supplementary Fig. 6A-B**) while the three other patient variants (p.G63A, p.V74F, p.F137L) showed intermediate growth relative to the wild-type rescue. The growth of one gnomAD variant (p.M131I) was similar to the wild-type rescue, while p.R48W and p.G103S both showed less growth relative to the wild-type rescue. The three patient variants

with intermediate growth at 100mM $CaCl_2$ and the three gnomAD variants were then tested at 200mM $CaCl_2$ (**Supplementary Fig. 6C-D**). Significantly less growth was seen with the three patient variants compared to the wild-type rescue ($p < 0.0001$), while two gnomAD variants (p.R48W and p.M131I) were comparable to the wild-type rescue. p.G103S showed less growth relative to the other gnomAD variants (p.R48W and p.M131I), but still yielded a significantly larger eAUC (**Supplementary Fig. 6D**) compared to the best growing patient variant at 200mM $CaCl_2$, p.F137L (59.22 ± 2.278 vs. 45.63 ± 2.243, $p = 0.0006$, two sample t-test).

Assessment of Three Patient Variants in *C. elegans*

Next, we assessed the effects of a subset of patient *ATP6V0C* variants on neurological function using *C. elegans.* Worms express three orthologous genes to *ATP6V0C* in neurons, *vha-1, vha-2,* and *vha-3.* VHA-2 and VHA-3 have identical amino acid sequences and share 66.7% amino acid identify with ATP6V0C, while VHA-1 has slightly less homology to ATP6V0C at 63% amino acid identity. The variants that were selected for further analysis were distributed throughout the protein, showed tolerance to 5mM $CaCl_2$ in the yeast growth assay, and were identified in patients with severe neurocognitive deficits and poly-medicated epilepsy. Specifically, we studied p.F137L (corresponding to p.F143L in VHA-2) and p.G63A and p.L150F (corresponding to p.G69A and p.L156F, respectively, in VHA-3*)*. A fourth strain carrying the p.A95T variant (corresponding to p.A101T in VHA-2) was generated but caused sterility in homozygous worms and was not studied further.

Worms expressing each variant were shorter and smaller than N2 (wild-type) controls at day 1 of adulthood, indicating a morphological delay even in ideal physiological conditions ($p < 0.05$, one-way ANOVA, **Fig. 6A-B**). When tested in liquid physiological M9 over a 4-hour period, movement of day 1 young adult worms with each mutation was comparable to N2 worms (**Fig. 6C**)**.** However, when motor function was examined under osmotic stress

conditions (350mM NaCl), mutants expressing p.G63A and p.F137L exhibited significantly reduced movement scores when compared to N2 worms ($p < 0.01$, two-way ANOVA, **Fig. 6D**). Although mutants expressing p.L150F also exhibited less movement than N2 worms, this difference was not statistically significant ($p = 0.0869$).

We next compared paralysis and lifespan of each mutant strain with N2 worms when maintained on NGM plates under physiological conditions or exposure to osmotic stress (200mM and 300mM NaCl). All mutants showed greater levels of paralysis when compared to N2 worms over a 14-day period, and these differences were strongly exacerbated in the presence of osmotic stress ($p < 0.0001$, log-rank (Mantel–Cox) test, **Fig. 6E-G**). Lifespans of the mutant strains were also reduced when compared to N2 worms when maintained under physiological conditions and osmotic stress ($p < 0.0001$, log-rank (Mantel–Cox) test, **Fig. 6H-J**).

To compare fine motor phenotypes, we exposed the mutant strains and N2 worms to liquid M9 with 500mM NaCl for 30 minutes and analyzed movement using WormLab. Activity index and wave initiation were significantly increased in the mutant strains when compared to N2 worms ($p < 0.05$), but swimming speeds were not significantly altered, suggesting increased but uncoordinated movements ($p > 0.05$, one-way ANOVA, **Fig. 7A-C**).

To test if the mutant strains have an impairment in nervous system signaling, we added an acetylcholinesterase inhibitor, aldicarb, to NGM plates and scored the number of paralyzed worms over a 2-hour period. Aldicarb causes an accumulation of acetylcholine in neuromuscular junctions resulting in muscle hypercontraction and acute paralysis, and can be used to evaluate if there is dysfunction of either GABA or acetylcholine signalling.[52,53] To confirm proper aldicarb effect, we included unc-47(e307) and unc-64(e246) mutants. Unc-47(e307) mutants are hypersensitive to aldicarb due to the lack of a vesicular GABA transporter

gene (orthologous to *SLC32A1* in humans) required for GABA transmission.[54] Unc-64(e246) (orthologous to *STX1A* in humans) mutants have reduced cholinergic neurotransmission, making them resistant to aldicarb-induced paralysis.[55,56] Worms expressing each patient variant showed greater paralysis in presence of aldicarb, compared to N2 worms ($p < 0.0001$, log-rank (Mantel–Cox) test, **Fig. 7D**).

Discussion

In this study, we report the identification of heterozygous *ATP6V0C* variants in 27 patients with neurodevelopmental phenotypes. In general, this cohort of patients presented with development delay, early-onset epilepsy (mean age of onset: 24.6 ± 8.0 months), and varying severities of intellectual disability. Five patients with MRIs show hypoplasia or agenesis of the corpus callosum. Congenital cardiac abnormalities were also observed in four patients. Interestingly, congenital heart defects have been reported in patients with pathogenic variants in *ATP6V1A* and *ATP6V1E1*.[3]

ATP6V0C is an evolutionary constrained gene as reflected by the high degree of amino acid homology between the human and yeast orthologs (72%), human and worm orthologs (63-67%), and human and Drosophila orthologs (78%), and the low number of missense variants in gnomAD (n=21 compared to an expected 108.5).[31] Of the 18 unique patient missense variants, 16 are located in TM domains, with nine in TM4 which encompasses the p.E139 residue that is required for proton transport by the V-ATPase.[1] Consistent with evolutionary constraints on TM4, only one variant in gnomAD is located in this region of the protein (**Fig. 2C**).

Interestingly, four patients (Patients 4, 9, 15 and 19) were found to be mosaic for their identified *ATP6V0C* variant. Based on the available clinical information, the seizure phenotype

of these patients may be less severe than for those with a germline variant (**Table 1**). Patient 4 (p.M53R) has seizure-like episodes that started at 14 months, but are not supported electrographically, Patient 15 (p.I132N) had seizure onset at 12 years of age, and Patient 19 (p.G142D) has not reported any seizure or seizure-like episodes. In contrast to the other mosaic patients, Patient 9 (p.A95T) had seizure onset at 10 months. p.A95T also resulted in decreased V-ATPase activity in yeast (**Fig. 5**) and sterility in homozygous worms (**Supplemental Table 4**). The timing of the post-zygotic mutation event, and the affected tissues, can have a large influence on phenotypic presentation and severity in patients with somatic mosaicism, underlying differences in clinical presentation between patients with germline and mosaic variants.[57] Previous work has demonstrated the utility of identifying somatic mosaicism for clinical and genetic counseling outcomes in patients.[58]

Nine copies of ATP6V0C and one copy of ATP6V0B assemble to form the intramembrane c-ring of the V-ATPase which uses a rotary mechanism to translocate protons across the membrane (**Fig. 1**).[21] Normally, frameshifting variants are predicted to cause NMD of the mutant mRNA, which would result in reduced protein levels. However, two of the four frameshift variants (c.340_355del16 and c.352_362delins) are located in last exon of *ATP6V0C* and are thus expected to escape NMD. The two frameshift variants in exon 2 may also escape NMD given the proximity of c.134_135delCT to the start codon and c.214delG being within 50bp of the last exon-exon junction (**Fig. 2A**).[59] Additionally, modeling showed that outward facing missense variants might act as a 'stone in the gear' between ATP6V0C and ATP6V0A inhibiting the rotatory mechanism, consistent with a dominant negative effect and the mechanism of action of V-ATPase inhibitors such as bafilomycin and archazolid **(Fig. 4A-B)**.[45,60] Therefore, we speculate that missense variants and those predicted to escape NMD act via a dominant negative mechanism, while nonsense variants and microdeletions containing *ATP6V0C* act via haploinsufficiency as demonstrated by our Drosophila data (**Fig. 3**).

However, additional studies, including the quantification of mRNA levels associated with each variant, are needed to delineate disease mechanisms more clearly.

Twelve disease-associated missense variants were examined in yeast. When the uptake of LysoSensor was measured, we saw that nine variants were associated with little to no fluorescence, indicating significant reduction or loss of V-ATPase activity. Higher levels of fluorescence were seen when the p.G63A, p.F137L, and p.L150F patient variants were expressed (**Fig. 5A, Supplementary Fig. 4**). Growth curves generated by yeast expressing the 12 patient variants mirrored observations from the LysoSensor assay (**Supplementary Fig. 5)**, with most variants resulting in little or no growth, and intermediate levels of growth observed with the p.G63A, p.V74F, p.F137L, and p.L150F variants (**Fig. 5F**). To further examine the effect of these intermediate variants on developmental and neurological function, we modeled p.G63A, p.F137L, and p.L150F in worms. Expression of all three variants resulted in morphological delay as indicated by reduced body size and length at day 1 of adulthood (**Fig. 6A-B**). Mutant worms also exhibited greater levels of paralysis and decreased lifespan when compared to N2 worms, and these phenotypes were exacerbated under osmotic stress (**Fig. 6E-J**). Mutants also exhibited increased activity and wave initiation rates, but speed was unaltered, suggestive of hyperactive and uncoordinated movement (**Fig. 7A-C**). The p.A95T variant which showed almost no V-ATPase function when tested in yeast (**Fig. 5**), resulted in homozygous sterility in worms, suggestive of a greater impact on V-ATPase function.

Additionally, we functionally examined, in yeast, three variants from gnomAD (p.R48W, p.G103S, p.M131I) that had high CADD scores and were predicted to be damaging by SIFT or Poly-Phen2 which contrasts the assumption that population variants would be benign (**Supplementary Table 5**). Expression of p.R48W and p.M131I resulted in growth that was more similar to the wild-type rescue compared to patient variants at 5mM $CaCl_2$ and did not significantly differ from wild-type rescue as higher concentrations of $CaCl_2$ were tested

(**Fig. 5F, Supplementary Fig. 6**). p.G103S, which had the highest CADD score of the gnomAD variants tested, resulted in significantly decreased growth compared to the wild-type rescue across all $CaCl_2$ concentrations tested (**Fig. 5F, Supplementary Fig. 6**). Nevertheless, p.G103S still yielded a significantly larger eAUC when compared to the best growing patient variant (p.F137L), suggesting the possibility of a level of decrease in V-ATPase activity that can be tolerated. However, we cannot exclude the possibility that mild clinical features could be associated with p.G103S or other rare gnomAD variants. Additional testing of population variants could establish the minimum level of V-ATPase activity required to maintain normal function. Such information would also aid in variant classification when novel patient variants are identified in the future.

The cellular mechanisms that explain the clinical features in patients with pathogenic variants in *ATP6V0C* are not yet known. However, given the importance of acidification driven by the V-ATPase in many cellular processes, it is likely that several pathways are impacted. Firstly, the acidification of SVs within the central nervous system by the V-ATPase allows transporters, such as VGLUTs and VGAT, to load their respective cargo.[61,62] Our modeling data predicts that outward facing patient variants would interfere with the interaction between ATP6V0C and ATP6V0A (**Figure 4**). Interestingly, patients with pathogenic *ATP6V0A1* variants (encoding ATP6V0A) present with developmental delay, epilepsy, intellectual disability and cerebellar atrophy, similar to patients with pathogenic *ATP6V0C* variants.[15] Recent work has shown that primary cortical neurons from *Atp6v0a1*$^{A512P/A512P}$ mice, modeling a variant identified in a patient, have decreased SV neurotransmitter content and form fewer synapses.[15] Given the functional interaction between ATP6V0C and ATP6V0A1, we speculate that synaptic defects likely contribute to disease pathology in patients with pathogenic *ATP6V0C* variants. These defects may also be independent of the ATPase activity of the V_1

domain as the V_0 domain is involved in neurotransmitter release independent of its acidification of SVs.[63-65]

The V-ATPase also plays an important role within the trans-Golgi network (TGN) and inhibition of V-ATPase driven acidification can lead to improper trafficking and sorting of various membrane bound proteins, including neuropeptides and neuropeptide receptors.[66-68] Additionally, pathogenic variants in *SLC9A7* in patients with developmental delay, intellectual disability, and muscle weakness have been shown to cause alkalization of the TGN.[69] Therefore V-ATPase dysfunction may also lead to altered synaptic signaling via disruption of trafficking and sorting of receptors to the synapse. Consistent with this prediction of altered synaptic signaling, worms expressing the p.G63A, p.F137L, and p.L150F variants displayed greater sensitivity to aldicarb and higher rates of paralysis compared to N2 worms (**Fig. 7D**).

Lastly, perturbations of lysosomal and autophagy pathways may also contribute to the epilepsy and neurodevelopmental phenotypes seen in these patients. The V-ATPase plays an essential role in acidifying endosomes, lysosomes, and autophagosomes which ultimately creates the environment needed for proper trafficking and maturation of endocytic organelles and acid hydrolase function within the autophagy pathway.[2,70] Previous work by Nakamura *et al.*[71] demonstrated that the V-ATPase is required for protein degradation from autophagic bodies in yeast vacuoles and Fassio *et al.*[14] showed impairments in autophagic flux caused by pathogenic variants in *ATP6V1A*. In recent years, the contribution of impaired autophagy to neurodegenerative and neurodevelopmental disorders, including epilepsy, has risen in importance.[14,72,73] We hypothesize that the epilepsy and other neurodevelopmental phenotypes seen in patients with pathogenic V-ATPase variants may be due to a combinatorial effect of impaired synaptic signaling, trafficking and sorting of various membrane bound proteins, and defects along the endomembrane system including the lysosomal/autophagy degradation

pathway. Further functional studies will be required to more thoroughly understand the mechanisms by which *ATP6V0C* variants lead to disease.

The prevalence of neurodevelopmental disorders, including epilepsy, resulting from variants in *ATP6V0C* is likely underestimated as this gene, to the best of our knowledge, is not currently included on commercially available epilepsy or intellectual disability gene panels. Of the 23 genes that encode for a subunit of the V-ATPase, twelve, including *ATP6V0C*, are associated with disease. Ten additional members of the complex are expressed in the central nervous system but are currently not associated with disease (**Supplemental Table 1**).[74] Screening of these genes for potential pathogenic variants in patients with disorders such as epilepsy and intellectual disability should be undertaken. Additionally, longitudinal studies in patients with *ATP6V0C* mutations, and the identification of additional patients, will play an important role in resolving the full spectrum of co-morbidities associated with altered ATP6V0C and V-ATPase function.

In summary, we report 27 patients with heterozygous *ATP6V0C* variants who presented with developmental delay, early-onset epilepsy, and intellectual disability. *In silico* modeling suggests that the majority of patient missense variants disrupt the interaction between the ATP6V0C and ATP6V0A subunits, and functional testing revealed that these variants decrease V-ATPase activity in yeast, and impair motor function, growth, and lifespan in worms. Further work is needed to fully elucidate the mechanism(s) by which altered *ATP6V0C* function lead to the range of observed clinical phenotypes, and whether other V-ATPase subunits not currently known to cause disease harbor pathogenic variants in patients with neurodevelopmental disorders without a current genetic diagnosis.

Acknowledgements

We would like to thank the patients and their families for their participation in this study. We would also like to thank Dr. Victor Faundez, Dr. Anita Corbett, Dr. Sara Leung, and Dr. Meleah Hickman (Emory University) for helpful advice and for providing reagents and equipment. Figure 1 was adapted from "V-ATP synthase", by BioRender.com (2022); retrieved from https://app.biorender.com/biorender-templates.

Funding

This study was supported by a training grant appointment to K.A.M (5T32GM008490), and an Emory University Research Council grant to A.E. J.B. is funded by a senior clinical investigator fellowship of the FWO-Flanders. This study was also supported in part by the Emory University Integrated Cellular Imaging Core (EICIC) and the Emory Integrated Genomics Core (EIGC) shared resources of Winship Cancer Institute of Emory University, NIH/NCI (award number: P30CA138292), the Canadian Rare Disease Models and Mechanisms Network (RDMM), Citizens United for Research in Epilepsy (339143), the Telethon Undiagnosed Diseases Program (TUDP; GSP15001), the Broad Institute of MIT and Harvard Center for Mendelian Genetics (Broad CMG) funded by the National Human Genome Research Institute, National Eye Institute, and the National Heart, Lung and Blood Institute (UM1-HG008900 and R01-HG009141), and the National Institute for Neurological Disorders and Stroke (U01-NS077303-04S1 and R01-NS058721). The content is solely the responsibility of the authors and does not necessarily reflect the official views of the National Institutes of Health. This study was in part generated within the European Reference Network ITHACA, and uses data shared through RD-Connect, funded by the European Union (FP7/2007-2013, No. 35444).

Additionally, this research was made possible through access to the data and findings generated by the 100,000 Genomes Project. The 100,000 Genomes Project is managed by Genomics England Limited (a wholly owned company of the Department of Health and Social Care). The 100,000 Genomes Project is funded by the National Institute for Health Research and NHS England. The Wellcome Trust, Cancer Research UK and the Medical Research Council have also funded research infrastructure. The 100,000 Genomes Project uses data provided by patients and collected by the National Health Service as part of their care and support.

Competing interests

The authors report no competing interests.

Supplementary material

Supplementary material is available at *Brain* online.

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Figure legends

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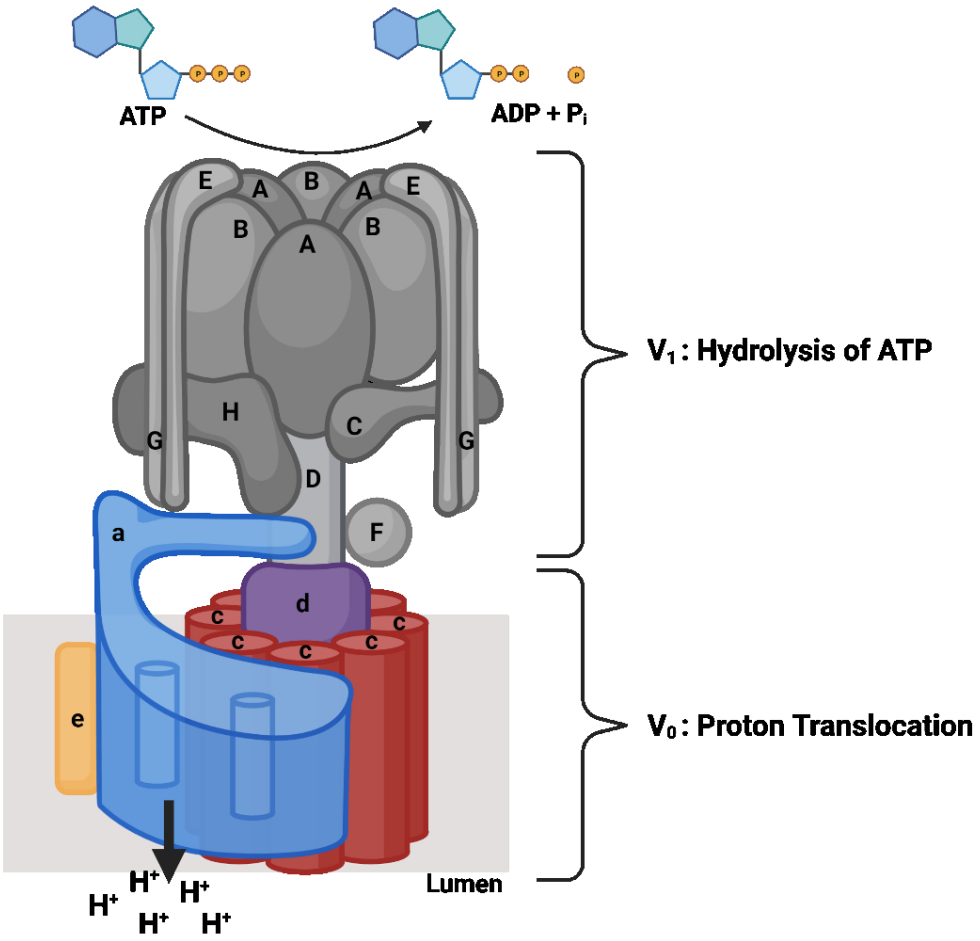
Figure 6. Expression of patient variants in *C. elegans* exacerbate motor dysfunction and reduce lifespan. (**A-B**) WormLab analysis of body length and size at day 1 of adulthood. All mutants are shorter and smaller than N2 controls. (**C-D**) Automated analysis of worm movement in liquid culture by WormTracker software. (**C**) In physiological M9 solution, all mutants show no motor deficits. (**D**) In presence of 350mM NaCl concentration the p.G63A ($p < 0.0001$) and p.F137L ($p < 0.0062$) mutants show reduced movement scores in liquid culture over 270 minutes. Reduced movement was also observed with the p.L150F variant, but this difference was not statistically significant ($p = 0.0869$). (**E**) All mutant strains showed increased paralysis over 14 days compared to N2 controls ($n = 313$-317 / strain, $p < 0.0001$). (**F-G**) In presence of osmotic stress (200 or 300mM NaCl) the paralysis phenotype is exacerbated, leading to almost 100% paralysis after 8 days for the p.G63A strain ($n = 246 – 260$ / strain, $p < 0.0001$). (**H**) All mutant strains exhibited reduced lifespan compared to N2 controls ($n = 219 – 233$ / strain, $p < 0.0001$). (**I-J**) All mutant strains have reduced lifespans in presence of osmotic stress compared to N2 controls. (200mM NaCl: $n = 182 – 228$ / strain. 300mM, $p < 0.0001$) (300mM NaCl: $n = 200 – 244$ / strain, $p < 0.0001$). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$ compared to N2 controls.

Figure 7. Patient mutations cause increased uncoordinated movement and neuronal signaling dysfunction in *C. elegans*. (**A-C**) Analysis of fine motor movement of worms after 30 minutes in 500mM NaCl liquid culture. Mutants show increased activity index and wave initiation (A&B), but swimming speed was not significantly altered (**C**). (**D**) Synaptic transmission was evaluated by exposing day 1 adult worms to aldicarb. Worms were scored over a 2-hour period for paralysis. All mutants were hypersensitive to aldicarb treatment compared to N2 worms (n = 236 – 296 / strain). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p <$ 0.0001 compared to N2 controls.



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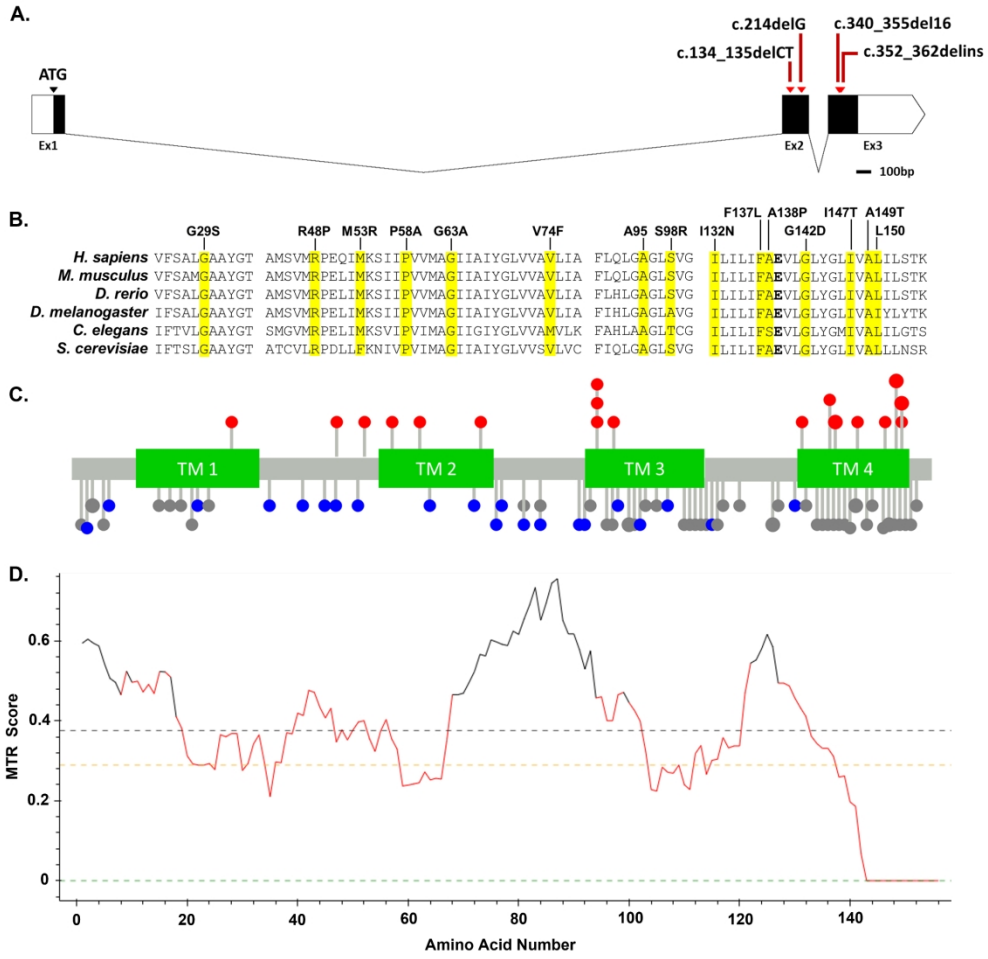

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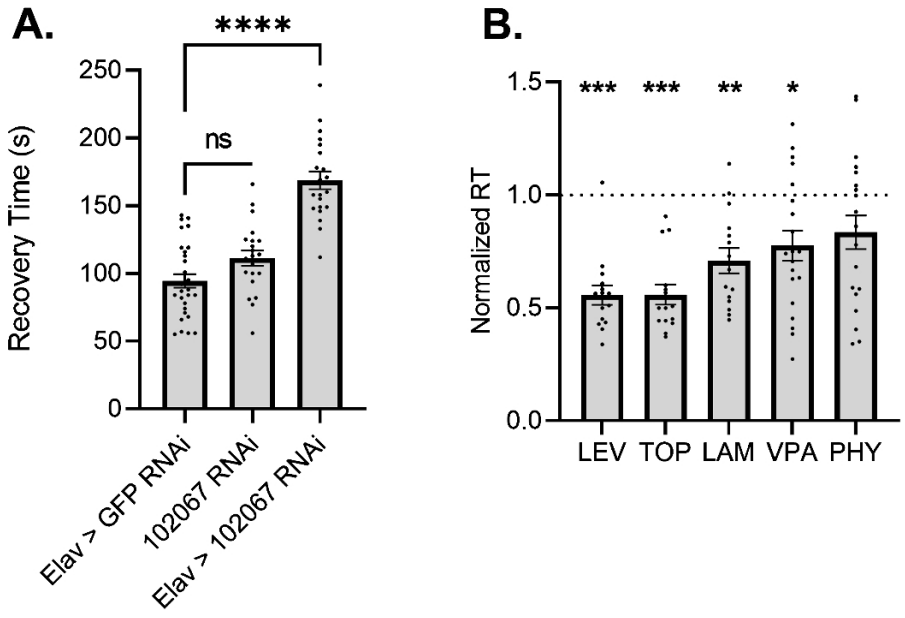

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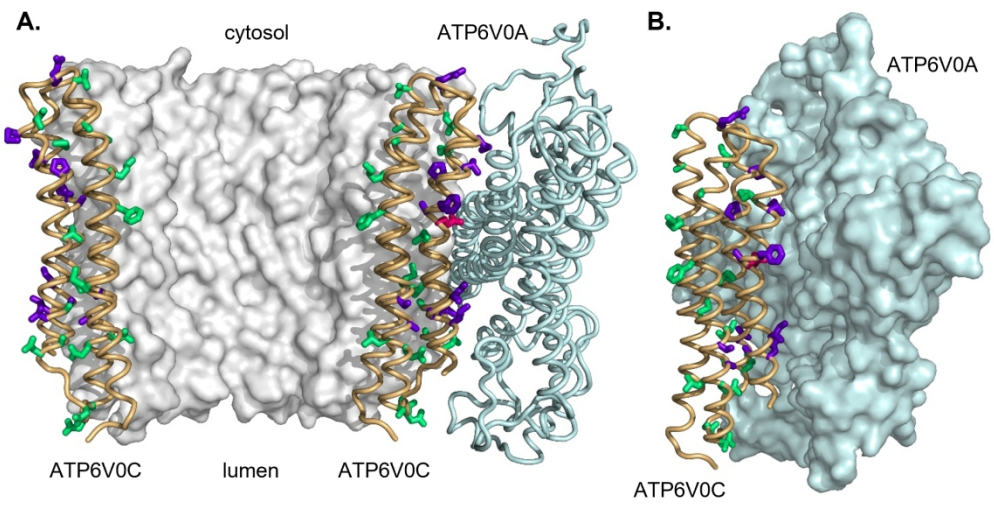

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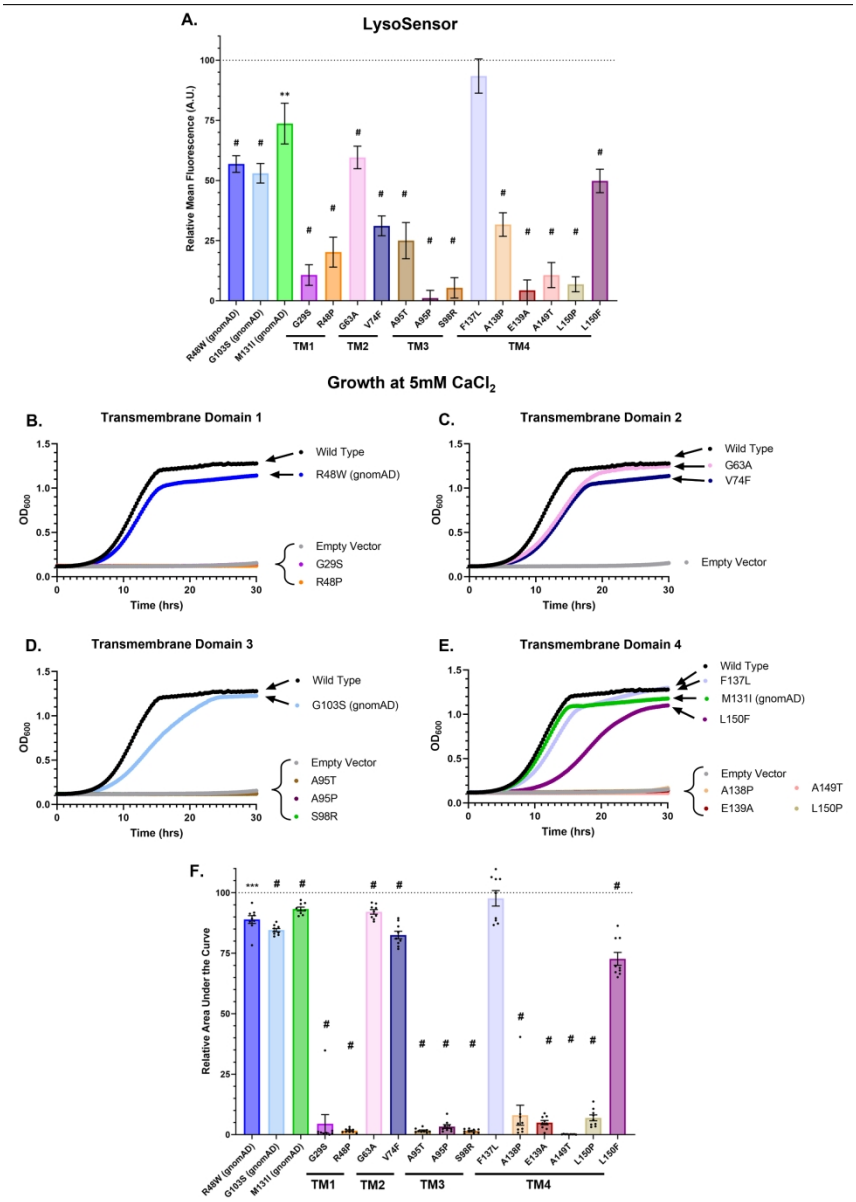

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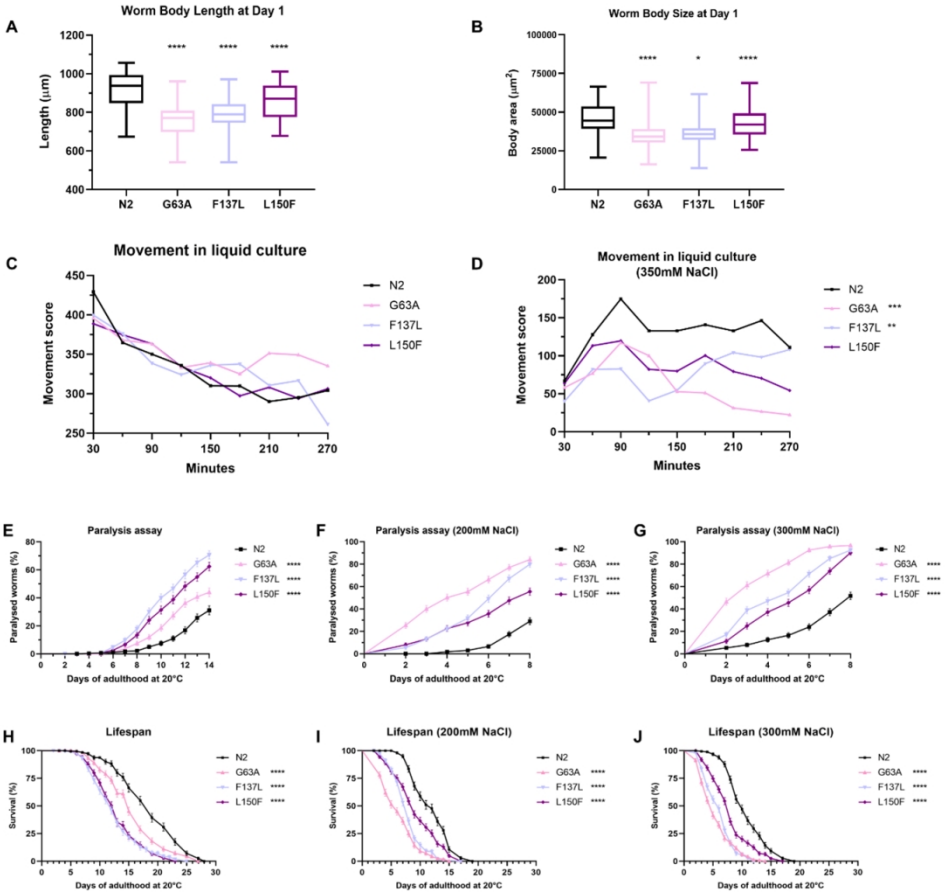

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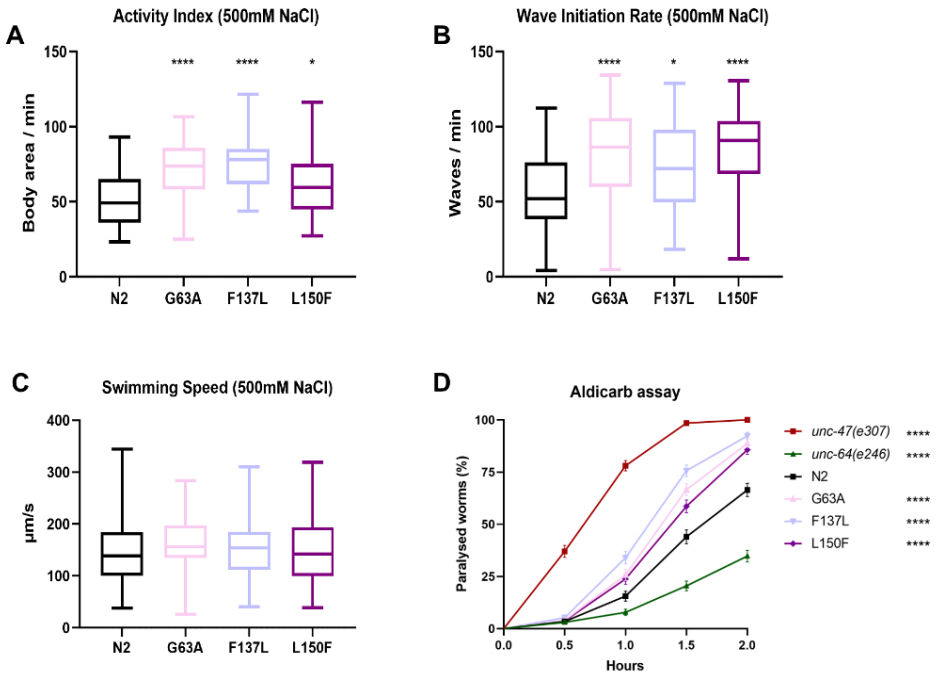

Figure 7. Patient mutations cause increased uncoordinated movement and neuronal signaling dysfunction in *C. elegans.* A-C) Analysis of fine motor movement of worms after 30 minutes in 500mM NaCl liquid culture. Mutants show increased activity index and wave initiation (A&B), but swimming speed was not significantly altered (C). D) Synaptic transmission was evaluated by exposing day 1 adult worms to aldicarb. Worms were scored over a 2-hour period for paralysis. All mutants were hypersensitive to aldicarb treatment compared to N2 worms (n = 236 – 296 / strain, $p < 0.0001$). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$ compared to N2 controls.

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Table 1 Clinical Presentation of Patients with *ATP6V0C* Variants

Patient	Variant[a]	CADD Score[b]	Inheritance	Seizures (Age at Onset)	Seizure Types	Developmental Delay	Intellectual Disability[c]
1[d]	c.85G>A; p.G29S	26.2	*de novo*	NA	NA	NA	NA
2[e]	c.134_135delCT; p.(S45CfsTer37)	NA	*de novo*	Yes (7mo)	GTCS, At, FDS, Myo, T	NA	Severe, with regression
3	c.143G>C; p.R48P	27.2	*de novo*	Yes (18mo)	NA	Yes, motor and speech	NA
4	c.158T>G; p.M53R	25.9	*de novo*, mosaic	No	NA	Yes	Too young for evaluation
5[f]	c.172C>G; p.P58A	23.1	NA	Yes	Cryptogenic focal	Yes, psychomotor	NA
6	c.188G>C; p.G63A	23.9	*de novo*	Yes (8mo)	Infantile spasms, GTCS, At, Myo	Yes, non-verbal	Severe
7	c.214delG; p.(V72WfsTer9)	NA	*de novo*	Yes	Infantile spasms	Yes	Too young for evaluation
8	c.220G>T; p.V74F	26	*de novo*	Yes (12mo)	GTCS, Ab, FOA	Yes, motor and speech	Severe
9	c.283G>A; p.A95T	26.2	*de novo*, mosaic	Yes (10mo)	GTCS, FOA, Febrile	Yes, regression to non-verbal	Profound
10	c.283G>C; p.A95P	24.6	*de novo*	Yes (10mo)	GTCS, staring	Yes, motor and non-verbal	Too young for evaluation
11	c.284C>T; p.A95V	23.7	*de novo*	Yes (5mo)	Febrile, Ab, Myo, T (nocturnal)	No	Moderate
12[d]	c.294C>A; p.S98R	13.2	*de novo*	NA	NA	NA	NA
13[g]	c.340_355del16; p.(D115AfsTer12)	NA	*de novo*	Yes (16mo)	Focal with secondary generalization	Yes, speaks only in short sentences	Yes
14	c.352_362delins; p.(V118HfsTer19)	NA	*de novo*	Yes (30mo)	GTCS, focal to bilateral TCS, Ab, FIA	Yes, motor and speech	Mild, regression in adulthood
15	c.395T>A; p.I132N	25.3	*de novo*, mosaic	Yes (12yr)	NA	Yes	Yes
16	c.409T>C; p.F137L	25.2	*de novo*	Yes (13mo)	GTCS, Myo, At, FOA	Yes, motor and non-verbal	Profound
17	c.412G>C; p.A138P	25.5	*de novo*	NA	TCS	Yes	NA
18	c.412G>C; p.A138P	25.5	*de novo*	Yes (6mo)	GTCS, multifocal	Yes, motor and speech	Too young for evaluation
19	c.425G>A; p.G142D	24.7	*de novo*, mosaic	No	NA	Yes, motor and non-verbal	Too young for evaluation
20	c.440T>C; p.I147T	23.3	*de novo*	Yes	NA	Yes, speech	Profound
21	c.445G>A; p.A149T	24.3	*de novo*	Yes (38mo)	Febrile, TCS, Myo, Ab	Yes, motor and speech	Mild
22	c.445G>A; p.A149T	24.3	*de novo*	Yes (6mo)	GTCS, At, TCS	Yes, motor and speech	Mild
23[d]	c.448C>T; p.L150F	25.1	NA	NA	NA	NA	NA
24	c.448C>T; p.L150F	25.1	*de novo*	Yes (6mo)	Infantile flexor spasms, T (w/ asymmetrical limb stiffening)	Yes, motor and speech	Profound
25	c.448C>T; p.L150F	25.1	*de novo*	Yes (6yr)	GTCS	Yes, motor and speech	Severe
26	c.449T>C; p.L150P	24.7	*de novo*	Yes (18mo)	Febrile, GTCS, T, At, Ab	Yes, fine motor	Mild

27[h]	c.467A>T; p.(Ter156LeuextTer35)	NA	*de novo*	Yes (24mo)	GTCS, TCS, At, afebrile	No	Yes, with regression

[a]Based on reference sequence NM_001694.4.
[b]Scores obtained using CADD GRCh37-v1.6.
[c]Intellectual Disability can usually be first assessed at 5 years of age
[d]Patients 1, 12, and 23 have severe neurodeveopmental diseases but detailed clinical information was unavailable.
[e]Previously published as Patient T1911 in Carvill *et al.*[28]
[f]ClinVar Variant: VCV000870676
[g]Previously published as DDD4K.04123 in DDD study[25]
[h]Previously published in Ittiwut *et al.*[24]
Abbreviations: Ab = absence, At = atonic, FDS = focal dyscognitive seizures, FOA = Focal onset aware (Partial), FIA = Focal impaired aware, GTCS = Generalized Tonic-clonic seizures, Myo = Myoclonic, NA = not available, T = Tonic, TCS = Tonic-clonic seizures

Subunit	Gene	Genomic Region	gnomAD Constraint Metrics[a]		Expression Profile[b]					Phenotype and Inheritance	MIM #	Reference
			Missense	Loss of Function	Brain	Kidney	Skin	Bone Marrow	Testis			
V_0a	*ATP6V0A1*	17q21.2	o/e = 0.52	o/e = 0.14	++	+	+	+	+	AD/AR DEE	NA	Aoto *et al.*[1]
	ATP6V0A2	12q24.31	o/e = 0.88	o/e = 0.54	+	+	+	+	+	AR Cutis Laxa (Type IIA)	219200	Kornak *et al.*[2]
	TCIRG1	11q13.2	o/e = 0.92	o/e = 0.63	+	+	+	++	+	AR Osteopetrosis	259700	Frattini *et al.*[3]
	ATP6V0A4	7q34	o/e = 0.89	o/e = 0.76	-	++	+	-	+	AR Distal RTA	602722	Smith *et al.*[4]
V_0c	*ATP6V0C*	16p13.3	o/e = 0.19	o/e = 0.00	+++	+++	+	++	++	AD Epilepsy	NA	Ittiwut *et al.*[5]
V_0c''	*ATP6V0B*	1p34.1	o/e = 0.53	o/e = 0.00	++	++	+	+++	+			
V_0d	*ATP6V0D1*	16q22.1	o/e = 0.45	o/e = 0.06	+++	++	+	++	++			
	ATP6V0D2	8q21.3	o/e = 1.16	o/e = 0.94	-	+	-	-	-	AR Skin and Joint Laxity	NA	Alazami *et al.*[6]
V_0e	*ATP6V0E1*	5q35.1	o/e = 0.94	o/e = 0.20	++	+++	++	++	++			
	ATP6V0E2	7q36.1	o/e = 0.85	o/e = 0.25	+++	+	+	+	+			
V_1A	*ATP6V1A*	3q13.31	o/e = 0.49	o/e = 0.18	+++	++	+	+	+	AR Cutis Laxa (Type IID) AD/AR IECEE 3	617403 618012	van Damme *et al.*[7] Fassio *et al.*[8]
V_1B	*ATP6V1B1*	2p13.3	o/e = 0.96	o/e = 0.64	+	++	+	-	+	AR RTA with deafness	267300	Karet *et al.*[9]
	ATP6V1B2	8p21.3	o/e = 0.59	o/e = 0.13	++	++	+	+	+	AD DDOD Syndrome AD Zimmerman-Laband Syndrome 2 AD Epilepsy AD DOORS Syndrome	124480 616455 NA NA	Yuan *et al.*[10] Kortum *et al.*[11] Shaw *et al.*[12] Beauregard-Lacroix *et al.*[13]
V_1C	*ATP6V1C1*	8q22.3	o/e = 0.65	o/e = 0.45	++	+	+	+	+			
	ATP6V1C2	2p25.1	o/e = 0.85	o/e = 0.62	+	+	++	+	+	AR Distal RTA	NA	Jobst-Schwan *et al.*[14]
V_1D	*ATP6V1D*	14q23.3	o/e = 0.72	o/e = 0.53	++	++	+	+	+			
V_1E	*ATP6V1E1*	22q11.21	o/e = 0.59	o/e = 0.20	+++	+++	++	++	++	AR Cutis Laxa (Type IIC)	617402	Alazami *et al.*[6]
	ATP6V1E2	2p21	o/e = 1.14	o/e = 0.59	+	+	+	+	+			
V_1F	*ATP6V1F*	7q32.1	o/e = 0.81	o/e = 0.67	+++	+++	++	++	+++			
V_1G	*ATP6V1G1*	9q32	o/e = 0.77	o/e = 0.40	++	+++	+	++	++			
	ATP6V1G2	6p21.33	o/e = 0.72	o/e = 0.59	+++	+	+	+	+			
	ATP6V1G3	1q31.3	o/e = 0.90	o/e = 0.40	-	+	-	-	-			
V_1H	*ATP6V1H*	8q11.23	o/e = 0.78	o/e = 0.39	++	++	+	+	+	AD Short Stature and Bone Loss	NA	Zhang *et al.*[15]

Table S1 – Genes encoding V-ATPase subunits in humans.

[a]gnomAD constraint metrics are a ratio of observed variants (o) over expected number (e) of variants. Values less than 1 indicate less variation is seen than expected, suggestive of evolutionary constraint or intolerance to variation.

[b]Based on human RNA-seq data from normal tissue, accessed through NCBI Gene.[16] Expression was classified into four categories based on mean RPKM values: -, 0.0 ≤ RPKM ≤ 0.99; +, 0.1 ≤ RPKM ≤ 24.99; ++, 25 ≤ RPKM ≤ 49.99; +++, RPKM ≥ 50.

Shaded rows represent genes with no known disease association.

Abbreviations: AD = autosomal dominant; AR = autosomal recessive; DEE = developmental and epileptic encephalopathy; DOOR = deafness, onychodystrophy, osteodystrophy, and mental retardation; IECEE = Infantile or early childhood epileptic encephalopathy; NA = not available; RTA = renal tubular acidosis.

		Patient 2[c]	Patient 3	Patient 4	Patient 5
Variant[a]		c.134_135delCT	c.143G>A	c.158T>G	c.172C>G
Protein Change		p.(S45CfsTer37)	p.R48P	p.M53R	p.P58A
Sex		Male	Female	Female	Male
Birth Growth Parameters		NA	Wt:1814g L:40.6cm	L: 48.3cm	NA
Age at Last Visit		8yr	17yr	4yr 1mo	NA
Growth Parameters at Last Visit	**Height**	NA	<3rd percentile	96.3cm (-1 SD)	NA
	Weight	NA	<75th percentile	11.9kg (-2.4 SD)	NA
	HC	NA	NA	47cm (-1.7 SD)	NA
Seizures?		Yes	Yes	No	Yes
Seizures Controlled?		NA	Yes	NA	NA
Current AED(s)		NA	Levetiracetam	None	NA
Previous AED(s)		NA	NA	None	NA
ID, DD		Severe ID with regression	Walked at 2.5yrs, speech between 3-4 years	3yr 11mo: no sentences, only 15 words Crawled at 13 months and walked at 2yr	Psychomotor delay
Behavior		NA	ASD	Tantrums, communication related	NA
Dysmorphisms		NA	Micrognathia, high palate, low posterior hairline, earlobe creases, prominent nasal bridge, tapering fingers	Long palpebral fissures, long eyelashes, persistent fetal finger pads	NA
EEG		GSW, MFD	NA	14 mo: Normal	NA
MRI		Normal	NA	30 mo: normal	Cerebellar vermis hypoplasia
Other		NA	Hypotnoia; Pulmonary valve stenosis; bipolar disorder	Hypotonia; seizure-like episodes from 14mo (freezing and eye-rolling) temporary and self-resolved- Not supported as seizures by EEG.	Dental enamel defects
Site for sequencing		NA	GeneDx	GeneDx	CeGaT Praxis für Humangenetik, Tübingen, Germany
WES or WGS		WES	Trio WES	Trio WES	NA
Library Capture		SeqCap EX Human Exome Library v2.0	NA	NA	NA
Sequencing		Illumina HiSeq	NA	NA	NA
Alignment		BWA	NA	NA	NA
Variant calling, filtering, and annotation		GATK	NA	NA	NA
Reference for exome method		Carvill *et al.*[17]	NA	NA	ClinVar Accession: VCV000870676.5
ACMG/AMP Classification[b]		Likely pathogenic (PS2, PM2, PM4)	Likely pathogenic (PS2, PM2, PP2, PP3)	Likely pathogenic (PS2, PM2, PP2, PP3)	Likely pathogenic (PM2, PM6, PP2, PP3)

		Patient 6	Patient 7	Patient 8	Patient 9
Variant[a]		c.188G>C	c.214delG	c.220G>T	c.283G>A
Protein Change		p.G63A	p.(V72WfsTer9)	p.V74F	p.A95T
Sex		Male	Female	Male	Male
Birth Growth Parameters		Wt: 2235g	Wt: 3240g L: 52cm Hc: 34cm	Wt: 3374g	Wt: 4lbs 6oz (Twin 3lbs 12oz)
Age at Last Visit		12yr 10mo	12mo	8yr	20yr
Growth Parameters at Last Visit	**Height**	167cm (+1.5SD)	74cm (+ 0.15 SD)	136cm (-0.65 SD)	68in (+1.5 SD)
	Weight	32kg (-3 SD)	8.8kg (-1.6 SD)	40.6kg (+1.2 SD)	107lbs (-1.3 SD)
	HC	48cm at 10yr (-3.8 SD)	43.8cm (-0.95 SD)	53cm (-0.9 SD)	53.3cm (-0.9 SD)
Seizures?		Yes	Yes	Yes	Yes
Seizures Controlled?		No	NA	NA	No
Current AED(s)		Lamotrigine, Levetiracetam	None	Carbamazepine, Zonisamide, Clobazam	Lamotrigine, Topiramate
Previous AED(s)		Vigabatrin, Pyridoxine, ACTH, Topiramate	None	Sodium valproate, Lamotrigine	Phenobarbital, Levetiracetam, Carbamazepine, Clonazepam, Ketogenic diet
ID, DD		Severe ID, non-verbal (at 5.5 yrs, Griffith development scale and Merrill Palmer R show results corresponding to 3-6 months)	Maintain head upright: 4mo, Sitting at 11mo, Babbling starting at 11-12mo	Severe ID (first words at 3-4 yrs, 50 single words at 8yrs) Sat independently at 6-8 months and walked at 13 months	Profound ID, Delayed speech milestones with regression
Behavior		Head banging, hair pulling	Too young for evaluation	ASD, ADHD, food seeking	ASD
Dysmorphisms		Microcephaly, small chin	Frontal bossing, low set and floppy ears, hypertelorism, mildly high palate, downslanting palpebral fissures, single transverse palmar crease	No	Thenar hypoplasia noted in hands, relative microcephaly
EEG		At onset: hypsarrhythmia. Primary generalized epileptic abnormality.	Normal	4yr: Bifrontal pattern of low amplitude beta activity	EEG 2002: 4 habitual seizures, ¾ arose in L hemisphere, ¼ arose in R hemisphere EEG 2011- 1 habitual seizure, arose on R hemisphere
MRI		21 mo: Widened liquor spaces, thin corpus callosum and delayed myelination.	<1yr: mild ventricular dilation	Normal	2yr: Normal
Other		Muscle weakness; scoliosis; feeding difficulties and gastrostomy; cryptorchidism; slightly thickened left ventricular wall; muscle biopsy at 10 mo showed combined complex I and IV defect in Oxidative Phosphorylation pathway	Frequent urinary infections; heart murmur; heterozygous de novo chromosome 20 deletion of 2.3Mb (q11.22q11.23) likely involved in the delayed development and dysmorphism	Loose stool as infant	NA
Site for sequencing		Centre for Inherited Metabolic Diseases, Karolinska University Hospital, Sweden	Blueprint Genetics, Finland	100000 Genomes	GeneDx
WES or WGS		WGS	Trio WES	WGS	Trio WES
Library Capture		Illumina TruSeq DNA PCR-free	NA	Illumina TruSeq DNA PCR-free	NA
Sequencing		Illumina HiSeq x Ten	NA	Illumina HiSeq 2500	NA
Alignment		BWA	NA	Isaac	NA
Variant calling, filtering, and annotation		GATK, VEP, Vcfanno, Genmod with MIP 8.2	NA	Platypus	NA
Reference for exome method		NA	NA	100000 Genomes Project[18]	NA
ACMG/AMP Classification[b]		Likely pathogenic (PS2, PM2, PP2, PP3)	Likely pathogenic (PS2, PM2, PM4)	Likely pathogenic (PS2, PM2, PP2, PP3)	Likely pathogenic (PS2, PM2, PP2, PP3)

		Patient 10	Patient 11	Patient 13[d]
Variant[a]		c.283G>C	c.284C>T	c.340_355del16
Protein Change		p.A95P	p.A95V	p.(D115AfsTer12)
Sex		Female	Male	Male
Birth Growth Parameters		Wt: 3.5 kg	Wt: 3.4kg L: 48cm Hc: 34.9 cm	NA
Age at Last Visit		4yr	25 yr	15yr
Growth Parameters at Last Visit	**Height**	115.5cm (+3.3 SD)	171cm (-0.78 SD)	NA
	Weight	19.3kg (+1.2 SD)	72kg (+0.18 SD)	NA
	HC	5th percentile	59cm (+2.7 SD)	55cm (+0.07 SD)
Seizures?		Yes	Yes	Yes
Seizures Controlled?		Has breakthrough seizures	Breakthrough tonic seizures at night	Yes, for 10 years
Current AED(s)		Oxcarbazepine, Topiramate	Oxcarbazepine, Valproic Acid, Levetiracetam	Lamotrigine
Previous AED(s)		Phenobarbital, Levetiracetam	Clobazam, Lamotrigine, Topiramate, Zonisamide, Phenobarbital, Vigabatrin	None
ID, DD		Sat without support at 12 months. At last visit, non-verbal and non-ambulatory (crawls).	Moderate ID, Sat independently at 9 months and walked at 15 months. First words at 14 months with sentences at 38 months.	Moderate to severe developmental delay. Speaks in short sentences, reads some words and recognizes some shapes.
Behavior		Picky eater	ASD, ADHD, aggression	ASD
Dysmorphisms		Round face, widely set eyes, midface hypoplasia, epicanthal folds, somewhat prominent ear lobes	None noted	No
EEG		17hrs at 10 months: Mildly abnormal with mild excessive slowing and probable post-ictal slowing on one occasion. Routine at 10.5 and 13 months: Mildly abnormal due to slowing. ~23hr at 16, 26, and 31 months: normal Prolonged at 37 months: Abnormal due to slowing, 3 electroclinical seizures observed; two consistent with partial seizures.	Background slowing, multifocal epileptiform activity with severe persistence	NA
MRI		10 mo: Normal 34 mo: Bilateral hippocampal sclerosis	Normal	NA
Other		Hypotonia; “Rett-like” episodes of hyperpnea/tachypnea; hand clasping behaviors without apraxia	Hypotonia starting at 15mo with gait ataxia and intentional tremor present; aggressiveness during adulthood that requires medication	Waddles; right side weaker than left with no clear cause; hypertrophic cardiomyopathy with moderate LVOT; mitral valve prolapse; mild-moderate mitral valve regurgitation with moderate mitral stenosis; previous symptoms for cryptorchidism; compound heterozygous for variants in *LZTR1*
Site for sequencing		Invitae, with re-analysis of raw data at Penelope Undiagnosed and Rare Program, University of Utah	Blueprint Genetics	Deciphering Developmental Disorders Study
WES or WGS		WES	Trio-WES	WES
Library Capture		NA	NA	Agilent SureSelect 55MB Exome Plus
Sequencing		NA	Illumina	Illumina HiSeq
Alignment		NA	BWA	BWA
Variant calling, filtering, and annotation		Sentieon	GATK, VcfAnno. VEP	GATK, SAMtools, Dindel, CoNVex, DeNovoGear, VEP v.2.6
Reference for exome method		NA	NA	Deciphering Developmental Disorders Study[19]
ACMG/AMP Classification[b]		Likely pathogenic (PS2, PM2, PP2, PP3)	Likely pathogenic (PS2, PM2 PP2, PP3)	Likely pathogenic (PS2, PM2, PM4)

		Patient 14	Patient 15	Patient 16	Patient 17
Variant[a]		c. 352_362delinsCATCGGCATCGTGGGGGACGCTGGC	c.395T>A	c.409T>C	c.412G>C
Protein Change		p.(V118HfsTer19)	p.I132N	p.F137L	p.A138P
Sex		Female	Female	Male	Female
Birth Growth Parameters		NA	Wt: 2409g L: 45.7cm	WT: 9lbs 6oz (90 percentile) L: 21 in (90 percentile)	NA
Age at Last Visit		34yr	13yr	17.5yr	9yr
Growth Parameters at Last Visit	**Height**	NA	NA	184.8cm (+1.5 SD)	NA
	Weight	NA	22.68kg (-3.5 SD)	64.6kg (+0.07 SD)	NA
	HC	56.5cm (+1.97 SD)	NA	56cm (+0.63 SD)	NA
Seizures?		Yes	Yes	Yes	Yes
Seizures Controlled?		NA	No	No	NA
Current AED(s)		Clobazam	Levetiracetam, Lamotrigine	CBD, Clobazam, Phenytoin, Levetiracetam	NA
Previous AED(s)		Valproate, Carbamazepine, Levetiracetam, Clonazepam	No	Topiramate, Zonisamide, Depakote, Lorazepam, Carbamazepine, Clonazepam	NA
ID, DD		Mild ID	Crawling at 17mo, walking at 6yr (on toes). Non-verbal, unable to follow simple commands	Profound ID, non-verbal, delayed motor milestones, walks with minimal support	Severe developmental delay
Behavior		ASD, pyschoses (>30 yrs)	Tantrums	Stereotypies	NA
Dysmorphisms		No	Microcephaly, mild synophrys, large mouth, macroglossia, coarsened facial features	Flat occiput, deep set eyes, wide-spaced teeth, full lips, two branchial arch pits on the right side of neck	NA
EEG		NA	NA	Slowing and disorganization of the background, frequent multifocal sharps, focal epileptiform abnormalities	NA
MRI		Small white matter changes in left hemisphere	12 yr: normal	9yr: diffuse supratentorial and infratentorial volume loss	NA
Other		Strange odor, especially before or after GTCS; increased amino acids (glycine, alanine and proline) in plasma.	Noisy breathing; mild ataxia	Broad-based ataxic gait; hypotonia; Ketogenic diet failed; Type I Diabetes diagnosed at 17yrs	Neonatal apneic episodes
Site for sequencing		UMC Utrecht, Netherlands	GeneDx	The Children's Hospital of Philadelphia	EGL Genetics
WES or WGS		WES	Trio Autism Xpanded Panel	WES	WES
Library Capture		Agilent SureSelect Clinical Research Exome V2	NA	Agilent SureSelect XT Clinical Research Exome Kit	Agilent SureSelect Clinical Research Exome V1
Sequencing		Illumina NovaSeq 6000	NA	Illuminia HiSeq 2000 or 2500	Illumina HiSeq
Alignment		BWA	NA	NA	PEMapper
Variant calling, filtering, and annotation		GATK, Alissa Interpret Clinical Informatics Platform	NA	In-house, custom-built bioinformatics pipeline v.CWES-2.2	PECaller, Bystro
Reference for exome method		NA	NA	NA	NA
ACMG/AMP Classification[b]		Likely pathogenic (PS2, PM2, PM4)	Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PP2, PP3)

		Patient 18	Patient 19	Patient 20
Variant[a]		c.412G>C	c.425G>A	c.440T>C
Protein Change		p.A138P	p.G142D	p.I147T
Sex		Male	Female	Male
Birth Growth Parameters		2300g	Wt: 3515g L: 50.8cm	NA
Age at Last Visit		16mo	26mo	17yr
Growth Parameters at Last Visit	**Height**	81cm (+0.4 SD)	84cm (-0.89 SD)	166cm (-1.2 SD)
	Weight	9.3kg (-1.8 SD)	9.24kg (-2.7 SD)	57.2kg (-0.79 SD)
	HC	43.5cm (-3.4 SD)	41.5cm (-4.3 SD)	50.2cm (+0.5 SD)
Seizures?		Yes	No	Yes
Seizures Controlled?		NA	NA	No
Current AED(s)		Topiramate, Clonazepam, Levetiracetam	None	Clobazam, Rufinamide, CBD
Previous AED(s)		None	None	Topiramate, Zonisamide, Sodium valproate, Levetiracetam, Lamotrigine
ID, DD		Delayed motor and speech milestones	Rolling at 6mo, siting at 14mo. 26mo: non-verbal, no self-feeding, walks with orthotics and assistance	Profound ID (no speech)
Behavior		None	Screams to indicate wants	Autistic traits
Dysmorphisms		Microcephaly	Microcephaly, periorbital fullness, shortened nasal bridge, triangular nasal tip, retrognathia, long first toes, cortical thumbs	Deep set eyes, prominent brows, deviated nose from breaking. (Many features also seen in unaffected father).
EEG		NA	NA	14yr: Abnormal due to moderate slow diffuse slowing of background rhythms, rare bifrontal and generalized low amplitude spikes in sleep, and cluster of brief generalized tonic seizures.
MRI		7 mo: delayed myelination, hypoplastic corpus callosum, frontal atrophy	10 mo: Pineal region cyst	4.7yr: Diffuse cerebral atrophy with diffuse T2 hyperintense signal involving white matter bilaterally. Bilateral hippocampal sclerosis.
Other		Hypotonia; dystonic posturing of upper limbs; poor eye contact	Hypotonia	Frequent falling
Site for sequencing		Copenhagen, Denmark	Gene Dx	Children's Hospital Los Angeles
WES or WGS		WES	Trio WES	Trio WES
Library Capture		Twist Human Core Exome Kit	NA	Agilent SureSelect Exon V6 plus custom mitochondrial genome capture kit
Sequencing		Illumina NovaSeq 6000	NA	NA
Alignment		BWA	NA	NA
Variant calling, filtering, and annotation		GATK and VarSeq	NA	Alissa
Reference for exome method		NA	NA	NA
ACMG/AMP Classification[b]		Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PP2, PP3)

		Patient 21	Patient 22	Patient 24
Variant[a]		c.445G>A	c.445G>A	c.448C>T
Protein Change		p.A149T	p.A149T	p.L150F
Sex		Male	Male	Male
Birth Growth Parameters		Wt: 3300g	Wt: 3390g	Wt: 3005g (+0.23 SD)
Age at Last Visit		5yr 8mo	16yr	11yr 6mo
Growth Parameters at Last Visit	**Height**	109cm (-0.75 SD)	180cm (+1.2 SD)	NA
	Weight	17.2kg (-1.2 SD)	79.6kg (+1.4 SD)	30.9kg (-1.2 SD)
	HC	48cm (-2.4 SD)	NA	49cm (-3.9 SD)
Seizures?		Yes	Yes	Yes
Seizures Controlled?		Yes, for 1 year	Yes, since 14.5yrs old	3-4yrs with ketogenic diet and topiramate
Current AED(s)		None	Levetiracetam, Lamotrigine	Topiramate
Previous AED(s)		Valproate	Levetiracetam with Topiramate	Sodium valproate, Carbamazepine, Prednisolone, Vigabatrin, Lamotrigine, Clobazam, Gabapentin, Levetiracetam, Rufinamide, Phenytoin, Ketogenic diet, Perampanel
ID, DD		Mild ID (IQ 71)	Mild Spoke 25 words at 3yrs	Profound ID (no words or sentences). Sat independently at 11 months, but not walking
Behavior		None	ADHD	ASD-like sensory, self-biting and scratching
Dysmorphisms		Microcephaly	Ears a bit low set, beaked nose (shared with mother)	Low columella, beaked nose, downturned mouth, plagiocephaly
EEG		Normal EEG background	From 6mo to 7yrs, several done. Many normal, four showing spikes, sharp waves (2 Hz), bifronto-temperal-centralt. From 7yrs to current: EEGs have all been normal	Early EEG reported to be normal. Developed left sided epileptiform activity and a left anterior temporal onset to clinical seizures. Interictal EEG shows excess of slow for age.
MRI		Normal	4yr: delayed myelination	Delayed myelination
Other		viral cerebellitis with transient ataxia at 3y; hypernasal speech	Valgus deformities of the feet	Weaned off ketogenic diet after recurrence of seizures and development of Staghorn calculus and renal calculi thought to be secondary to ketogenic diet; poor weight gain/oral intake; mild scoliosis; no enamel on teeth; soft brittle nails
Site for sequencing		CME Leuven, Belgium	Amplexa Genetics, Denmark	100000 Genomes
WES or WGS		Trio WES	Trio WES	WGS
Library Capture		SeqCap EZ Exome v3; Roche	Twist Human Core Exome Multiplex Enrichment Kit	Illumina TruSeq DNA PCR-free
Sequencing		Illumina NovaSeq 6000	Illumina NovaSeq 6000	Illumina HiSeq 2500
Alignment		BWA	BWA	Isaac
Variant calling, filtering, and annotation		GATK, Alissa Interpret Clinical Informatics Platform	Freebayes	Platypus
Reference for exome method		NA	NA	100000 Genomes Project[18]
ACMG/AMP Classification[b]		Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PM5 PP2, PP3)

		Patient 25	Patient 26	Patient 27[e]
Variant[a]		c.448C>T	c.449T>C	c.467A>T
Protein Change		p.L150F	p.L150P	p.(Ter156LextTer35)
Sex		Male	Female	Female
Birth Growth Parameters		Wt: 2780g (25th percentile)	NA	NA
Age at Last Visit		10yr 5mo	24yr	16yr
Growth Parameters at Last Visit	**Height**	125.2cm (-2.2 SD)	175cm (-1.8 SD)	146cm (-2.5 SD)
	Weight	25kg (-1.82 SD)	83.4kg (+1.6 SD)	NA
	HC	49cm (-3.5 SD)	NA	58cm (+3.3 SD)
Seizures?		Yes	Yes	Yes
Seizures Controlled?		Yes	Yes	No
Current AED(s)		VPA	Lamotrigine, Brivaracetam, Clobazam, CBD	Topiramate, Clonazepam, Levetiracetam, Lamotrigine
Previous AED(s)		None	Levetiracetam, Sodium valproate, Topiramate, Rufinamide	NA
ID, DD		Severe ID. Sat independently at 11 months and walked independently at 4 years. First words at 4 yr, but no full sentences.	Mild ID and fine motor delay. Walked at 2 yrs and talked after 2 yrs.	ID with regression
Behavior		Autistic traits	Autistic traits	NA
Dysmorphisms		Bulbous nose	Beaked nose and low set ears	NA
EEG		Abnormal	2-2.5 Hz slow-spike wave discharges, paroxysmal generalized fast activity	7yrs: generalized spike-wave complexes 16yrs: frequent spike-slow waves originating in left frontal region
MRI		Normal	Corpus callosum agenesis/dysplasia	7, 9, and 16 yrs: Unchanged slightly smaller size of left hippocampus
Other		Scoliosis, proportionate short stature	Lennox-Gastaut Syndrome; s/p laser corpus callosotomy; vagal nerve stimulation; frequent drop attacks	NA
Site for sequencing		TIGEM, Pozzuoli, Italy	NA	Macrogen Inc.
WES or WGS		WES	NA	WES
Library Capture		Agilent SureSelect QXT Target Enrichment System	NA	NA
Sequencing		Illumina NovaSeq 6000	NA	NA
Alignment		VarGenius Pipelines	NA	NA
Variant calling, filtering, and annotation			NA	NA
Reference for exome method		Musacchia *et al.*[20]	NA	Ittiwut *et al.*[5]
ACMG/AMP Classification[b]		Pathogenic (PS2, PM1, PM2, PM5, PP2, PP3)	Pathogenic (PS2, PM1, PM2, PM5, PP2, PP3)	Likely pathogenic (PS2, PM2, PM4)

Table S2. Clinical and Sequencing Information for each patient.

Detailed clinical information was unavailable for Patients 1 (c.85G>A, p.G29S, *de novo*), 12 (c.294C>A, p.S98R, *de novo*), and 23 (c.448C>T, p.L150F).

[a]Based on reference sequence NM_001694.4.

[b]Classifications using criteria outlined by Richards *et al.*[21]

[c]Previously published as Patient T1911 in Carvill *et al.*[17]

[d]Previously published as DDD4K.04123 in the Deciphering Developmental Disorders Study[19]

[e]Previously published in Ittiwut *et al.*[5]

Abbreviations: ADHD = Attention Deficit Hyperactivity Disorder, ASD = Autism Spectrum Disorder, BWA = Burrows-Wheeler Aligner, CBD = Cannabidiol, GSW = Generalized spike-wave, GATK = Genome Analysis Toolkit, HC = Head circumference, L = length, LVOT = left ventricular outflow tract, MFD = Multifocal discharges, NA = not available, Wt = weight

Strain/Plasmid	Description	Human Allele	Source
vma3Δ (YEL027W)	*MATa leu2Δ ura3Δ his3Δ TRP1 met15Δ vma3Δ::kanMX*	-	Dharmacon
pRS316	*CEN6, URA3, amp^R*	-	Sikorski and Heiter[22]
pKM16	*VMA3* in pRS316, *CEN6, URA3, amp^R*	Wild type	This Study
pKM17	*vma3-R46P* in pRS316, *CEN6, URA3, amp^R*	p.R48W	This Study
pKM18	*vma3-G61A* in pRS316, *CEN6, URA3, amp^R*	p.G63A	This Study
pKM19	*vma3-A93T* in pRS316, *CEN6, URA3, amp^R*	p.A95T	This Study
pKM20	*vma3-F135L* in pRS316, *CEN6, URA3, amp^R*	p.F137L	This Study
pKM21	*vma3-A136P* in pRS316, *CEN6, URA3, amp^R*	p.A138P	This Study
pKM22	*vma3-E137A* in pRS316, *CEN6, URA3, amp^R*	p.E139A	This Study
pKM23	*vma3-L148F* in pRS316, *CEN6, URA3, amp^R*	p.L150F	This Study
pKM24	*vma3-L148P* in pRS316, *CEN6, URA3, amp^R*	p.L150P	This Study
pKM27	*vma3-R46W* in pRS316, *CEN6, URA3, amp^R*	p.R48W	This Study
pKM28	*vma3-G101S* in pRS316, *CEN6, URA3, amp^R*	p.G103S	This Study
pKM29	*vma3-M129I* in pRS316, *CEN6, URA3, amp^R*	p.M131I	This Study
pKM30	*vma3-V72F* in pRS316, *CEN6, URA3, amp^R*	p.V74F	This Study
pKM31	*vma3-A93P* in pRS316, *CEN6, URA3, amp^R*	p.A95P	This Study
pKM32	*vma3-S96R* in pRS316, *CEN6, URA3, amp^R*	p.S98R	This Study
pKM39	*vma3-G27S* in pRS316, *CEN6, URA3, amp^R*	p.G29S	This Study
pKM40	*vma3-A147T* in pRS316, *CEN6, URA3, amp^R*	p.A149T	This Study

Table S3 – Yeast Strains and Plasmids

Strain	Human Allele	*C. elegans* Gene	*C. elegans* Variant	*Source*
AP08	p.G63A	*vha-3*	p.G69A	This Study
AP09	p.L150F	*vha-3*	p.L156F	This Study
AP10	p.A95T	*vha-2*	p.A101T	This Study
AP11	p.F137L	*vha-2*	p.F143L	This Study

Table S4. *C. elegans* Strains and Variants
Note: The *C. elegans* A101T mutation caused sterility in homozygous *C. elegans* worms. Therefore, AP10 was not used in the assays.

gnomAD Variant[a]	c.142C>T; p.R48W	c.307G>A; p.G103S	c.393G>C; p.M131I
gnomAD count[b]	1	2	1
CADD Score[c]	21.2	24	23
Poly-Phen2[c]	Benign (0.235)	Probably Damaging (0.957)	Benign (0.168)
SIFT[c]	Deleterious (0.04)	Deleterious (0.05)	Deleterious (0.04)
Location	CL1	TM3	TM4

Table S5. gnomAD Variants Assessed in Yeast.
[a]Based on reference sequence NM_001694.4.
[b]Number of times observed in gnomAD (v.2.1.1) out of approximately 250,000 alleles.
[c]CADD, Poly-Phen2 and SIFT scores obtained from CADD GRCh37-v1.6
Abbreviations: CL = cytoplasmic loop, TM = Transmembrane domain

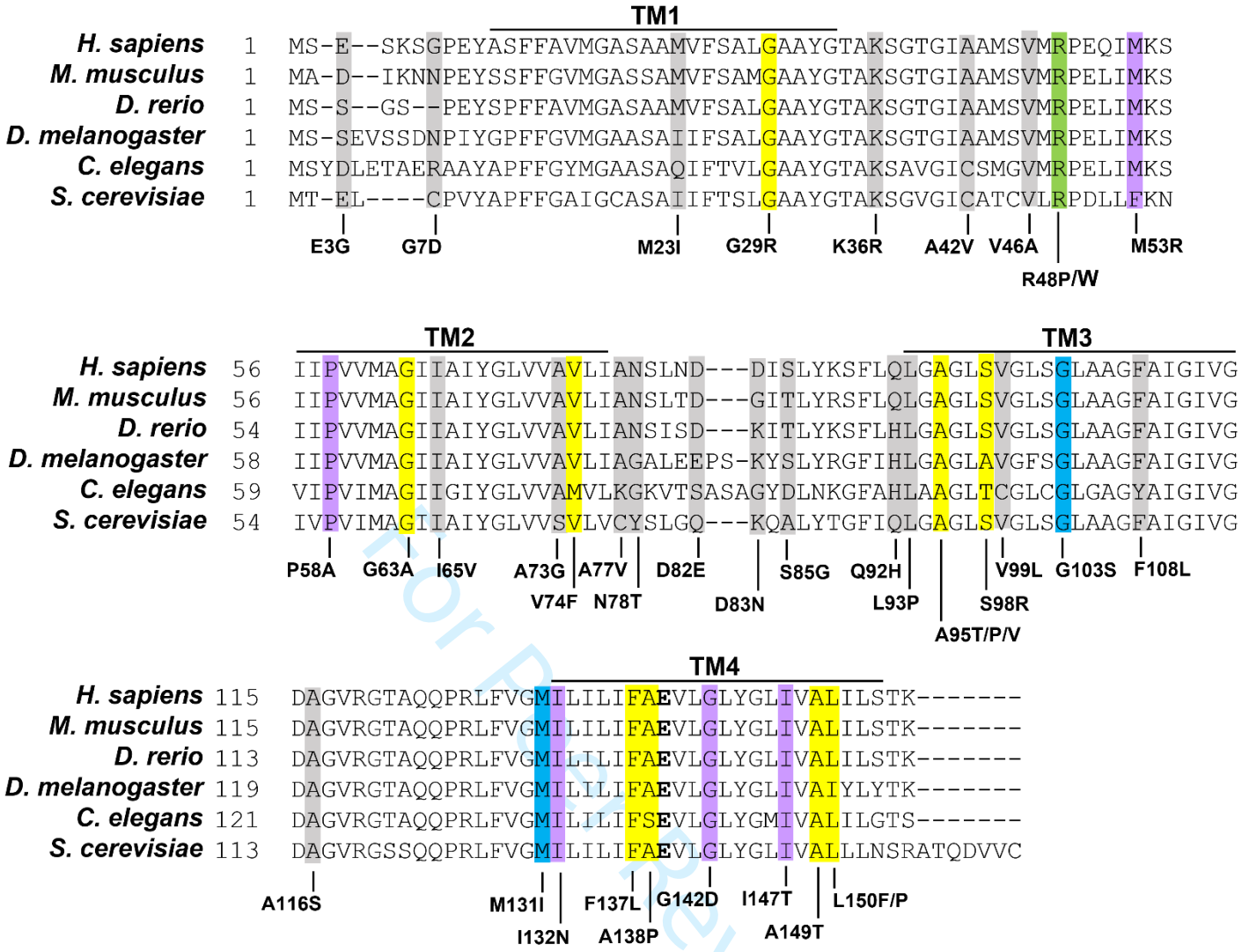

Figure S1. Alignment of human ATP6V0C with selected eukaryotic organisms.
Residues affected by missense changes in patients are highlighted in yellow (functionally tested) or pink (not tested). Residues highlighted in blue (functionally tested) and grey (not tested) represent variants from gnomAD (v.2.1.1). R48 (in green) is the location of a patient and gnomAD variant, p.R48P (tested) and p.R48W (tested), respectively. The bolded “E” represents the glutamate residue required for proton transport. Transmembrane regions are denoted by “TM”. The following protein sequences were used in the alignments: *H. sapiens*, NP_001685.1; *M. musculus*, NP_001348461.1; *D. rerio*, NP_991117.7; *D. melanogaster*, NP_476801.1; *C. elegans,* NP_499166.1; *S. cerevisiae,* NP_010887.3.

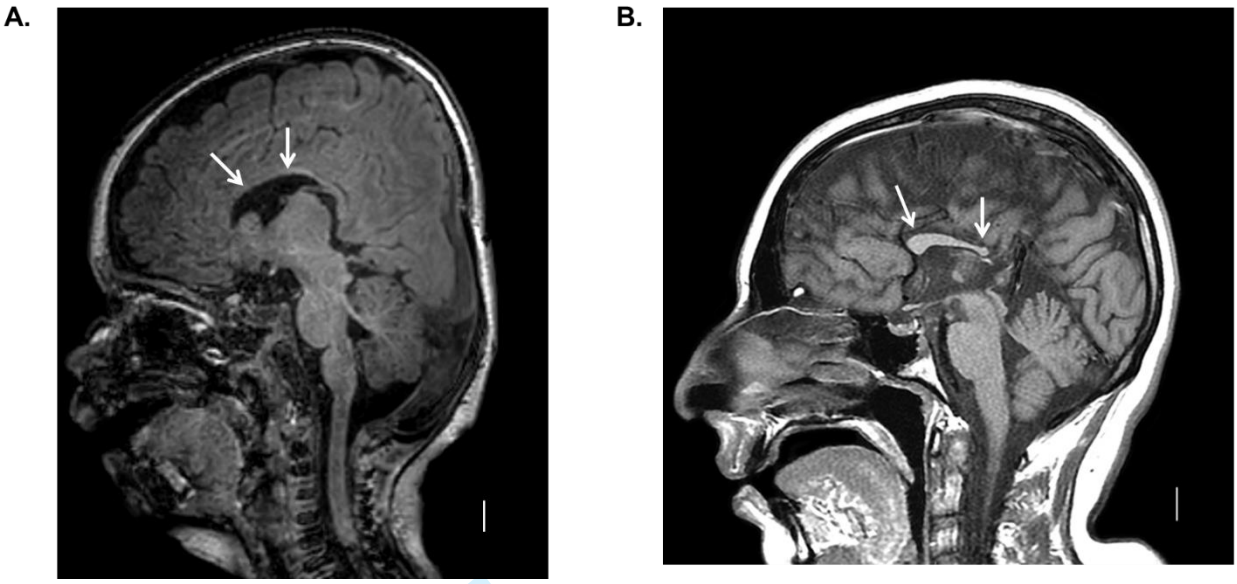

Figure S2. Magnetic Resonance Imaging of Patients.
A) Sagittal MRI from patient 18 demonstrating hypoplasia of the corpus callosum (arrows).
B) Sagittal MRI from patient 26 demonstrating moderately short corpus callosum with absent rostrum, tapered body and very small splenium (arrows).
Horizontal white bars in lower right indicate 1cm.

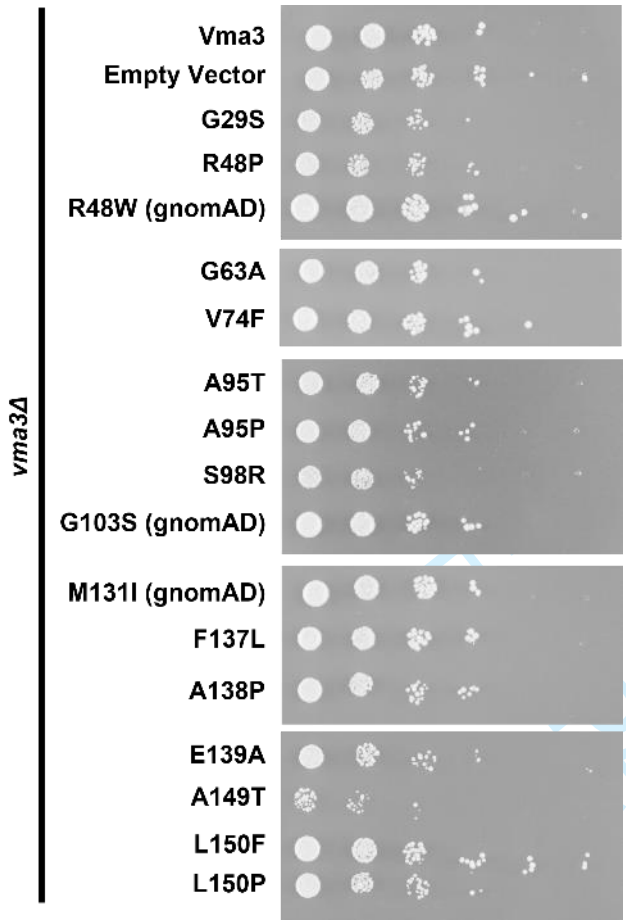

Figure S3. Transformants can Grow in Permissive Conditions.
Liquid cultures of the *vma3Δ* strain transformed with a wild-type plasmid or a plasmid expressing a patient variant were serially diluted and spotted onto SD-ura, pH 5.5 and grown at 30°C for 48hrs.

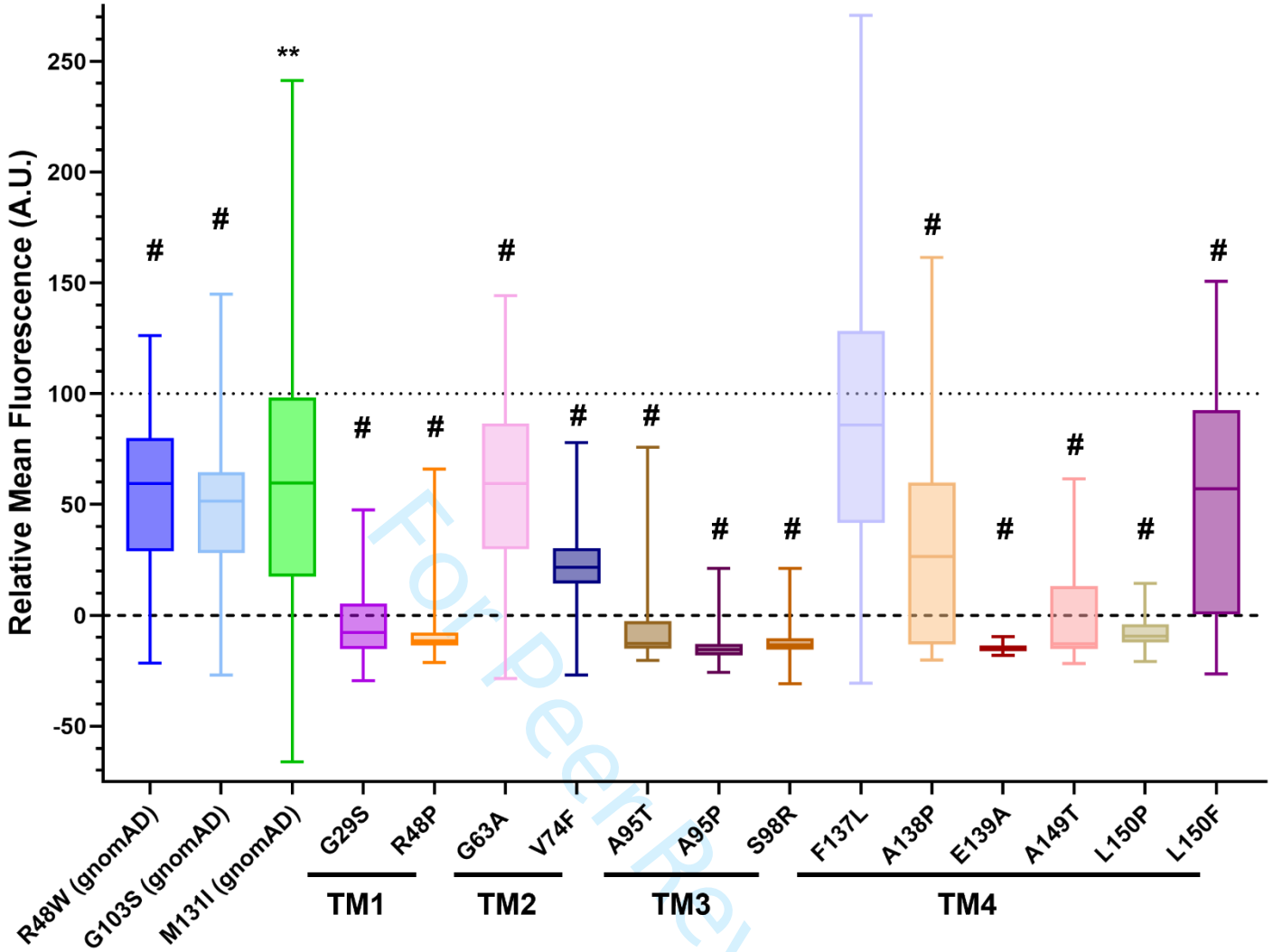

Figure S4. Box and Whisker Plot of LysoSensor Data.
Average fluorescent intensity for each variant. Variants are grouped based on their location within or proximity to the nearest transmembrane (TM) domain. Data was normalized with mean of WT as 100% (dotted line) and mean of empty vector as 0% (dashed line). Whiskers represent minimum and maximum, and boxes show the 1st to 3rd interquartile range with the median. A one sample t-test to a hypothetical mean of 100 was conducted with a Bonferroni correction (adjusted α level = 0.0003125). $^{**}p < 0.01$, $^{\#}p < 0.0001$. *p*-value for M131I is 0.0025 making it significant with our adjusted α level.

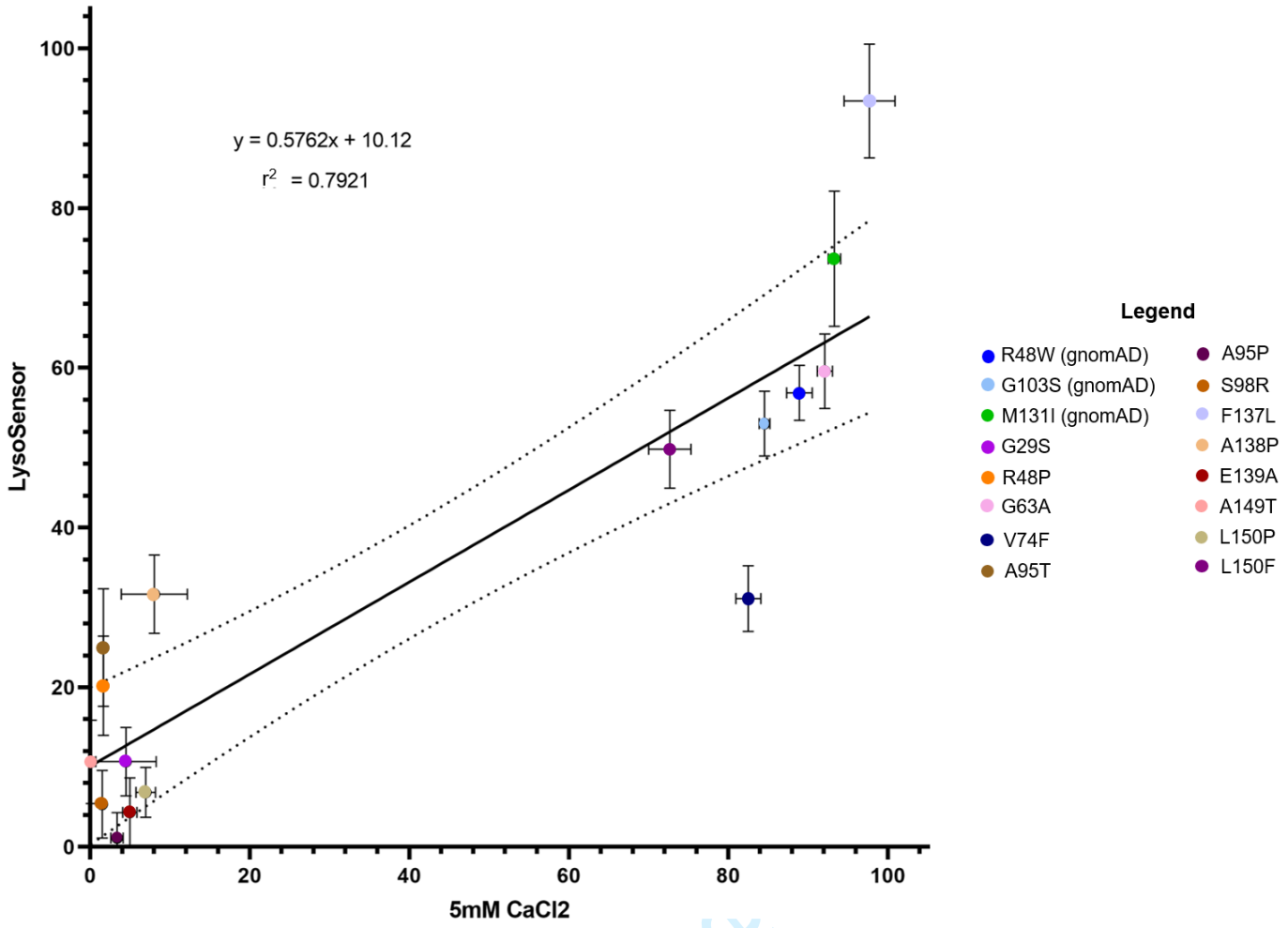

Figure S5. Correlation of 5mM $CaCl_2$ and LysoSensor Data for Each Variant.
Normalized eAUC (5mM $CaCl_2$) vs normalized mean fluorescence (LysoSensor). A linear regression was performed using GraphPad Prism (v9). Solid line represents the line of best fit for the mean of each variant with the 95% confidence interval denoted by dotted lines. Error bars represent SEM.

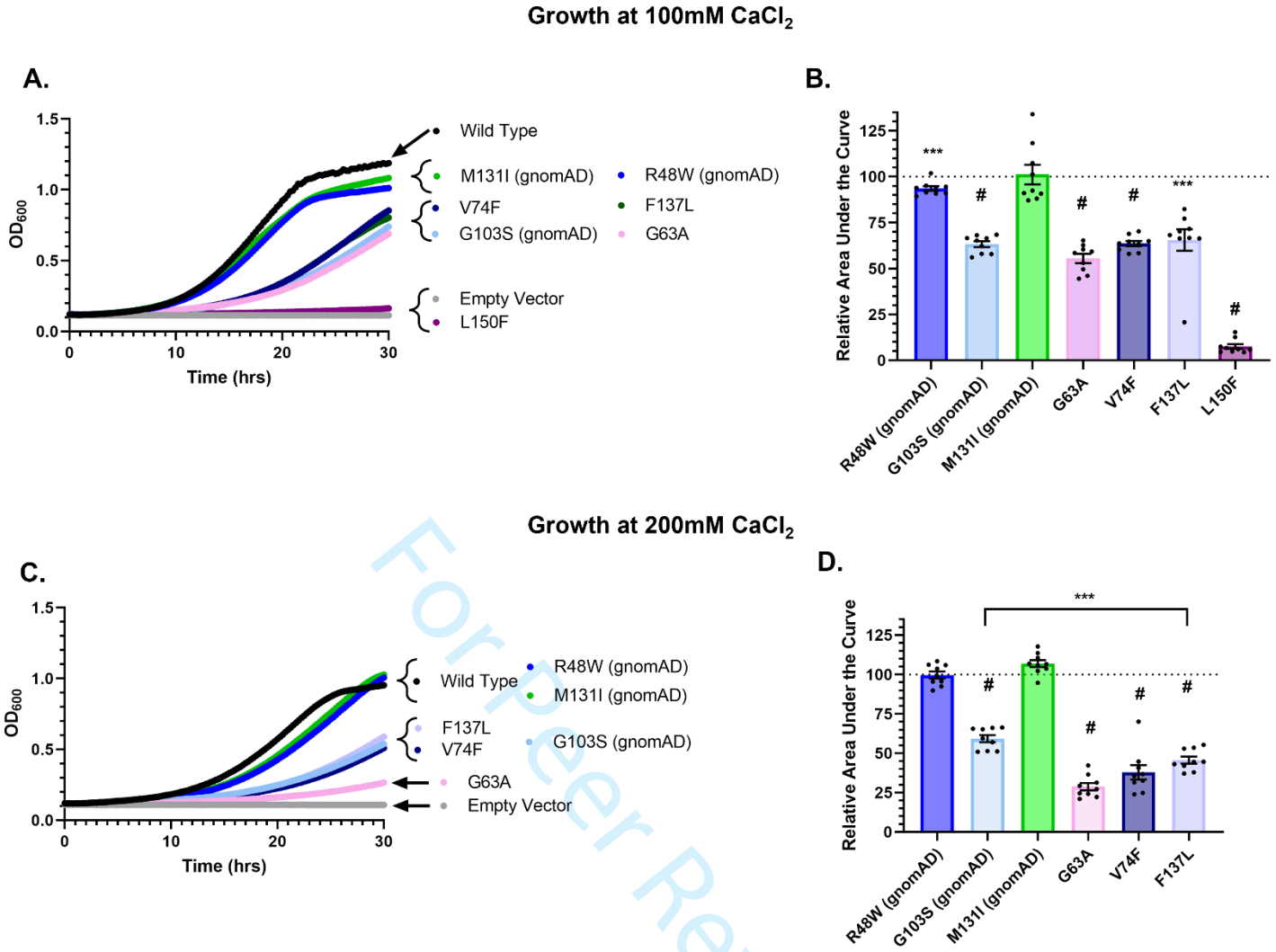

Figure S6. Growth of Selected Patient Variants at 100mM and 200mM $CaCl_2$.
Growth curves of *vma3Δ S. cerevisiae* expressing patient variants at A) 100mM $CaCl_2$ or C) 200mM $CaCl_2$. In all panels, wild type is shown in black and the empty vector in grey. Mean of 9 replicates per construct is shown with error bars omitted for clarity. B and D) Empirical area under the curve was calculated using GrowthCurver.[23] Data was normalized within each plate with wild type as 100% (denoted by dotted line) and empty vector as 0% and is shown as Mean ± SEM. A one sample t-test to a hypothetical mean of 100 was conducted with a Bonferroni correction (adjusted α level = 0.00714 for 100mM and 0.00833 for 200mM). ***p < 0.001, $^{\#}p$ < 0.0001.

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