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Developmental and epilepsy spectrum of *KCNB1* encephalopathy with long-term outcome

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Summary

Objective: We aimed to delineate the phenotypic spectrum and long-term outcome of individuals with *KCNB1* encephalopathy.

Methods: We collected genetic, clinical, EEG and imaging data of individuals with *KCNB1* pathogenic variants recruited through an international collaboration, with the support of the family association "KCNB1 France". Patients were classified as having developmental and epileptic encephalopathy (DEE) or developmental encephalopathy (DE). In addition, we reviewed published cases and provided the long-term outcome in patients older than 12 years from our series and from literature.

Results: Our series included 36 patients (21 males, median age: 10 years, range: 1.6 months to 34 years). Twenty patients (56%) had DEE with infantile-onset seizures (seizure onset: 10 months, 10 days-3.5 years), while sixteen (33%) had DE with late-onset epilepsy in 10 (seizure onset: 5 years, 18 months-25 years) and without epilepsy in 6. Cognitive impairment was more severe in individuals with DEE compared to those with DE. Analysis of 73 individuals with *KCNB1* pathogenic variants (36 from our series and 37 published individuals in seven reports) showed developmental delay in all with severe to profound intellectual disability in 67% (n= 41/61) and autistic features in 56% (n= 32/57). Long-term outcome in 22 individuals older than 12 years (14 in our series and 8 published individuals) showed poor cognitive, psychiatric and behavioral outcome. Epilepsy course was variable. Missense variants were associated with more frequent and more severe epilepsy compared to truncating variants.

Significance: Our study describes the phenotypic spectrum of *KCNB1* encephalopathy which varies from severe DEE to DE with or without epilepsy. Although cognitive impairment is worse in patients with DEE, long-term outcome is poor for most and missense variants are associated with more severe epilepsy outcome. Further understanding of disease mechanisms should facilitate the development of targeted therapies, much needed to improve the neurodevelopmental prognosis.

Keywords: drug resistant epilepsy; autism spectrum disorders; sudden unexpected death in epilepsy; developmental and epileptic encephalopathy; developmental encephalopathy; potassium channels

Key Points Box

- *KCNB1* encephalopathy has a wide phenotypic spectrum, typically with poor long-term cognitive, psychiatric and behavioral outcomes

- *KCNB1* pathogenic variants are associated with developmental and epileptic encephalopathies or developmental encephalopathies with or without epilepsy
- Patients with developmental and epileptic encephalopathy show a worse cognitive outcome, emphasizing the impact of early epilepsy
- Epilepsy is less frequent and less severe in individuals with truncating variants compared to those with missense variants

1. Introduction

Over the last decade, the large application of next-generation sequencing has significantly increased the discovery of genes involved in both neurodevelopmental disorders and epilepsy[1]. The International League Against Epilepsy introduced the term "Developmental and Epileptic Encephalopathy" (DEE) to define severe neurodevelopmental disorders in which developmental consequences arise directly from the underlying aetiology, which is often genetic, as well as from frequent epileptic activity[2]. The term "Epileptic Encephalopathy" alone applies to individuals without preexisting developmental delay where the adverse developmental impact is due to seizures and epileptiform activity[2,3]. The term "Developmental Encephalopathy" (DE) should be used for individuals presenting with developmental impairment without frequent epileptic activity causing regression or further slowing of development[2].

Pathogenic variants in ion-channel genes represent a major cause of DEE[4,5]. Despite the genetic heterogeneity, some strong phenotypes are emerging in relation to pathogenic variants in some specific genes as for *KCNT1*, *KCNQ2*, *SCN1A*, *SCN2A*[4]. *KCNB1* codes for the α subunit of the voltage-gated potassium channel subfamily 2 ($K_v2.1$)[6]. In 2014, *de novo* pathogenic variants in *KCNB1* were first recognized to cause infantile-onset epileptic encephalopathy in three patients[7]. Two series, including 6 and 25 individuals in total, have been reported, in addition to case reports[8–15]. Individuals exhibited global developmental delay, behavioral disorders and various epilepsies[8–15]. A few individuals had developmental

delay without seizures[11,16]. Outcome data is limited as few adults have been described. It has been suggested that truncating variants in the C-terminal domain correlate with less severe epilepsy outcome[11,16].

Here, we analyze a series of 36 individuals with pathogenic *KCNB1* variants to delineate the phenotypic spectrum of *KCNB1* encephalopathy. We explore genotype-phenotype correlations and long-term outcome to guide patient management and inform genetic and prognostic counseling.

2. Materials and methods

2.1. Individuals

Individuals with *KCNB1* pathogenic variants were collected through a large international collaboration between the network of the French Reference Centre for Rare Epilepsies and centers in Belgium, Italy, Spain, Luxembourg, New Zealand and Australia, with the support of the family association "KCNB1 France". For each individual, we collected information on medical and developmental history, epilepsy, clinical examination, EEG and brain imaging findings. The severity of intellectual disability (ID) was classified by the referring physician according to developmental scales used in their institution or based on clinical evaluation. We classified seizures and epilepsy types and, where possible, epilepsy syndromes according to the International League Against Epilepsy (ILAE) proposal[2,17]. Individuals were classified as having *KCNB1* developmental and epileptic encephalopathy (DEE) when epilepsy (seizures and EEG) resulted in developmental slowing or regression. Individuals were classified as *KCNB1* developmental encephalopathy (DE) when they had less active epilepsy, often with late onset seizures and without clear regression or slowing of development. The DE group also included individuals without seizures. Because of the limited number of patients and their broad age range, the cut-off age of 12 years were choose to look at long-term outcome in order to include a sufficient number of patient. Informed written consent was obtain for all participants for research participation, including the use of photographs, according to the human research ethics committee of each participating institution.

2.2. Variant analysis

KCNB1 variants were identified by targeted next generation sequencing gene panels or whole exome sequencing. Sanger sequencing confirmed single nucleotide variants and segregation analysis was performed in each family. We classified variants according to the

guidelines of the American College of Medical Genetics (ACMG)[18]. *KCNB1* variants were described according to HGVS variant nomenclature guidelines (http://varnomen.hgvs.org/)[19], using the reference sequence RefSeq NM_ 004975.2. Variants have been submitted to the ClinVar database (https://www.ncbi.nlm.nih.gov/clinvar/).

2.3. Literature review

Pubmed was searched for reports of individuals with *KCNB1* pathogenic variants by combining the terms "KCNB1" and "variants" or "mutations". Articles were reviewed and compared with variants listed in professional databases (Human Gene Mutation Database [HGMD], Biobase, and Qiagen). The accuracy of variant description was checked using Alamut 2.10 (Interactive Biosoftware).

2.4. Statistics

Descriptive data are represented as median (interquartile range). Statistical tests were performed using a 2-sided Fisher's exact test with statistical significance determined by $P < 0.05$.

3. Results

3.1. Series

3.1.1. Demographic data

Our cohort included 36 unrelated individuals (21 males) with *KCNB1* pathogenic variants (Table S1). Age at study ranged from 1.6 months to 34 years (median: 10 years, interquartile range: 6-15 years). Pregnancy and delivery were unremarkable for 32/36 (89%) individuals. Patient 19's mother reported decreased fetal movements and patient 23's mother suspected in-utero seizures. Emergency Caesarean section for fetal deceleration was performed at term for individuals 17 and 28, without neonatal distress.

3.1.2. Variants

Our series comprises 28 patients with previously reported *KCNB1* variants[16] and 8 new patients (Table S1). The 36 patients had 30 different *KCNB1* pathogenic variants, including 25 (83%) missense, four (13%) nonsense and one (3%) frameshift. Three variants were recurrent: p.Arg312His in five patients and p.Arg306Cys and p.Gly395Arg in two patients respectively. Individual 1 with p.Glu43Gly affecting the cytoplasmic N-terminal region also carried a *de novo* variant in *GABRA5* (p.Thr301Met), which encodes the alpha 5 subunit of the gamma-aminobutyric acid type-A ($GABA_A$) receptor. Both variants were

predicted to be damaging and thus considered pathogenic and contributing to the individual's phenotype[16]. Variants occurred *de novo* in 31/36 individuals. In four individuals (patients 2, 10, 25, 30), segregation could not be completed because parental samples were not available. Patient 36 inherited p.Arg583* from her heterozygous mother who had mild ID without epilepsy. The variant arose *de novo* in the mother.

3.1.3. Neurodevelopment

All individuals had developmental delay, recognized in the first year of life in 32/36 (89%) patients (Table S1). Intellectual disability ranged from mild in 5/36 (14%), to moderate (10/36, 28%), severe (19/36, 53%) and profound (2/36, 6%). Of 33/36 patients older than 3 years, 17/33 (52%) had no words, 9/33 (27%) used some words and 7/33 (21%) spoke short sentences. Orofacial apraxia was reported in 2/36 (6%). Behavioral and psychiatric disorders were reported in 28/34 (82%) including stereotypies and other autistic features in 18/34 (53%), uncontrolled aggression in 11/34 (32%) and impulsiveness or attention-deficit hyperactivity disorder (ADHD) in 13/34 (38%). Antipsychotic treatments were used in 8/36 (22%) and psychostimulants in 3/36 (8%) patients. In 12/36 (33%) patients aged 2-29 years, families reported sleep disorders, particularly frequent waking during nighttime sleep. Polysomnography was performed in 2 of them, revealing parasomnia and frontal motor seizures in patient 6 and central apnea in patient 23. 29/35 (83%) patients older than 2 years acquired independent walking at median age 24 months (interquartile range: 18-36 months, range 16-54 months).

3.1.4. Examination

Hypotonia was observed in 19/36 (53%) patients in infancy and varied in severity. Hyperlaxity and ataxia were each reported in 8/36 (22%) patients. Pyramidal signs, dystonia or choreoathetosis were each observed in 6/36 (17%) different patients. Normal head circumference was present in all but three patients who had acquired microcephaly reaching -2 to -3 SD. Two patients had a gastrostomy with some oral intake. Morphological analysis of 14 patients revealed minor dysmorphic features including sunken eyes in 13 and large median incisors in 6 (Figure 1). To note, patient 8 had more pronounced dysmorphic features. He had chromosomal microarray without evidence for copy number variants and, except for the KCNB1 pathogenic variant, no other pathogenic variant have been found on whole exome sequencing. He is the oldest patient (34 years) and morphological evolution over time has not yet been documented in this population.

3.1.5. Epilepsy

Thirty patients (30/36, 83%) had epilepsy (Table S1). Median age at seizure onset was 17 months (interquartile range: 8-35 months, range 10 days-25 years) with pre-existing developmental delay in all patients. Twenty patients (20/36, 56%) had *KCNB1* developmental and epileptic encephalopathy (*KCNB1* DEE), while sixteen (16/36, 44%) had *KCNB1* developmental encephalopathy (*KCNB1* DE), including 6 without epilepsy (Figure 2).

The 20 patients with *KCNB1* DEE had a median age at seizure onset of 10 months (interquartile range: 8-17 months, range 10 days-3.5 years). Eleven individuals showed developmental slowing or plateauing after seizure onset while 9 had developmental regression. The first seizure was generalized in 16 individuals (16/20, 80%) including epileptic spasms (n=6), tonic or tonic-clonic seizures (n=3), atypical absences (n=3), myoclonic (n=2) and atonic seizures (n=1). With increasing age, most individuals developed several seizure types: 15/20 (75%) had >2 seizure types and 12/20 (60%) >3 seizure types. Only 5 patients (5/20, 25%) could be classified into a specific epilepsy syndrome such as infantile spasms (n=3) and Lennox-Gastaut syndrome (n=2). The remaining 15 patients (15/20, 75%) had "unclassified DEE" with frequent multifocal epileptiform activity on EEG (Figure 3). Four individuals (4/20, 20%) had activation of EEG abnormalities during sleep. At follow-up, median age for individuals with *KCNB1* DEE was 9 years (interquartile range: 4-16, range 19 months-34 years). Fourteen patients (14/20, 70%) had drug-resistant epilepsy with daily seizures in 8/14, weekly in 4/14 and monthly in 2/14. Two patients with infantile spasms were in remission by 8 and 14 months respectively. Patients received a median of 7 antiseizure medications (ASM) (interquartile range: 3-10). Response to vigabatrin occurred in 5/7 patients with epileptic spasms. All five individuals receiving the ketogenic diet were responders.

In the 16 patients with *KCNB1* DE, 10 had epilepsy. The first seizure occurred at a median age of 5 years (interquartile range: 2-5 years, range 18 months to 25 years). Epilepsy was generalized in 3/10, focal in 3/10 and combined generalized and focal in 1/10. Three individuals only had a few motor seizures of unknown onset and did not require ASM. Seizures remitted in three patients at age 16 months, 6 and 12 years, respectively. Six patients aged 4.5 to 20 years had not had seizures.

ID and language disorder were more severe in patients with *KCNB1* DEE compared to those with *KCNB1* DE and epilepsy. Sixteen out of 20 patients with *KCNB1* DEE had severe to profound ID compared to 4/10 patients with *KCNB1* DE and epilepsy (P=0.04). Of patients older than 3 years, 13/17 with *KCNB1* DEE were non-verbal compared with 3/10

with *KCNB1* DE and epilepsy (*P*=0.04). However, we found no difference in independent walking and behavioral or psychiatric characteristics between these two groups.

3.1.6. MRI data

Twenty-five individuals (25/33, 76%) had a normal brain MRI performed at a median age of 3 years (interquartile range: 2-6) (Table S1). Patient 6 with *KCNB1* DE and focal epilepsy had two areas of focal cortical dysplasia (Figure 4). Brain MRI of patient 20 who did not develop epilepsy showed small bilateral periventricular heterotopia. Cortical and subcortical non-specific findings and moderate atrophy were reported in three patients. In patient 31 with *KCNB1* DEE, atrophy was probably progressive. He showed moderate atrophy on MRI at 7 years after a previous normal MRI at 2.5 years. In the other three patients, MRI showed delayed myelination at 3.5 years (patient 16), non-specific bilateral central tegmental tract hyperintensity on serial MRI (patient 24) and a mild brachycephaly (patient 26).

3.2. Analysis of all cases

In addition to our series of 36 individuals, 37 published individuals with *KCNB1* encephalopathy were identified in seven reports[7–15,20–25]. Taken together, this series of 73 individuals included 50 distinct *KCNB1* pathogenic variants. Variants typically arose *de novo* except for the maternally inherited variant p.Arg583* in patient 36. Variants were scattered throughout the KCNB1 protein with 27/50 (54%) located in the pore forming region (S5-S6 transmembrane domains). Thirty-nine variants (78%) were missense and 11 were truncating (22%). Eleven variants were recurrent in two to eight individuals (Figure 5). Median age was 9 years (interquartile range: 5-15, data available for n= 70/73). We summarized the epilepsy and developmental spectrum of all 73 individuals (55% males) (Table 1).

3.2.1. Phenotype-genotype correlation

Epilepsy was more frequent in individuals with missense variants (55/59) compared to those with truncating variants (8/13, *P*=0.008). Epilepsy was also more frequently drug-resistant in individuals with missense (25/34) compared to those with truncating variants (0/4, *P*=0.01). Epilepsy was less frequent in individuals with variants in the C-terminal domain (5/7 versus 4/61, *P*=0.0002). This was expected since all variants of the C-terminal domain were truncating. We observed no further correlations between the neurodevelopmental phenotype and the variant type or its position in the protein (Figure 5). Individuals with recurrent variants had a similar range of neurodevelopmental disorders. Their phenotypic spectrum ranged from DE with or without mild epilepsy to drug-resistant DEE (Figure 5).

3.2.2. Long-term outcome

We reviewed the long-term outcome of *KCNB1* encephalopathy in 22 patients older than 12 years: 14 from our series and eight published cases[11,13]. Median age was 17 years (interquartile range: 15-22 years, range 12-34 years). Nineteen patients (19/22) had epilepsy. Epilepsy beginning in infancy or early childhood remitted in 5 individuals who became seizure free at median age 11 years (interquartile range: 9-16 years) and ASM were progressively withdrawn. Three of them had *KCNB1* DE, one had *KCNB1* DEE and the last one from the literature cannot be classified. Duration of remission ranged from 2 to 24 years. Seizure frequency decreased over time in 3 individuals. Five individuals still had daily to weekly seizures; three evolved to Lennox-Gastaut syndrome, one previously had neonatal myoclonic DEE and the remaining two had unclassified DEE. One individual had a few sporadic seizures at age 25 years and was not treated. Epilepsy outcome was not documented in 5 individuals.

Developmental outcome was not constantly reported from previous literature reports. Seventeen patients (17/21, 81%) had severe developmental delay with no information for one patient. Three individuals, two aged 12 and one aged 20 years, did not have epilepsy and their ID varied from mild to severe. In the 18 patients with reported language skills, 11/18 (61%) were non-verbal, 4/18 (22%) spoke words and 3/18 (17%) used short sentences. Information on behavioral and/or psychiatric disorders was available in 19 individuals with reported disorders in 16/19 (84%). Seven of them required antipsychotic drugs. Finally, walking information was reported in 17 individuals with 13/17 (76%) walking independently, one with support and three needed a wheelchair.

Mortality did not appear to be increased as there was no history of sudden unexpected death in epilepsy (SUDEP) and only one individual with Lennox-Gastaut syndrome following a neonatal myoclonic DEE died at 17 years due to severe pneumonia.

4. Discussion

We report a large series of individuals with *KCNB1* encephalopathy, delineating the phenotypic spectrum and long-term outcome. This large series is the result of a successful collaboration between academia and family support group (family association “KCNB1 France”) taking from the shadow dozens of families and patients, in addition to a large international collaboration through seven tertiary epilepsy centers. Early developmental delay is universal with two-thirds of individuals having severe to profound ID. More than 80%

develop epilepsy. Autism spectrum disorder (ASD) and other psychiatric and behavioral disorders occur in more than half of individuals.

The most common phenotype, occurring in 56% cases, was *KCNB1* DEE with infantile-onset drug-resistant seizures associated with periods of developmental regression or plateauing. A range of seizure types may occur including epileptic spasms, generalized and focal seizures. *KCNB1* should now be included in epilepsy gene panels and interrogated for a pathogenic variant when performing genetic testing in patients with DEE.

In addition, we identified 10 individuals with *KCNB1* DE and epilepsy who presented later and had pharmaco-responsive epilepsy, without evidence of epileptic encephalopathy. These individuals showed better cognitive outcome compared to those with *KCNB1* DEE, emphasizing the impact of early onset seizures and severe epilepsy on neurodevelopment. Importantly, we studied 6 individuals aged 4.5-20 years who had not yet had seizures, along with three previously reported, confirming that *KCNB1* also causes early-onset DE without epilepsy.

The long-term outcome observed in 22 individuals older than 12 years from our current series and from literature showed that the natural history of epilepsy was highly variable, ranging from individuals with drug-resistant epilepsy to others in remission, allowing ASM withdrawal. Unfortunately, cognition remained poor with moderate to severe ID in most individuals. Patients also had severe expressive language disorder and frequent behavioral and psychiatric issues impacting on everyday life of the individuals, their caregivers and families.

Our study showed that truncating *KCNB1* variants were associated with less frequent and less severe epilepsy compared with missense variants. Of the nine individuals with truncating variants and available data, five did not develop seizures, while four had infantile spasms with remission on either vigabatrin or adrenocorticotropic hormone allowing cessation of ASM. This finding suggests that ASM can be withdrawn in individuals with *KCNB1* truncating variants whose seizures have remitted. This will limit potential side effects related to ongoing ASM use. All truncating variants were in the last exon and thus expected to produce a truncated protein rather than nonsense-mediated mRNA decay[26]. However, few functional studies have been performed to date with limited data on truncating variants. One recent study showed altered current density for two truncating variants when expressed as homotetramers but normalized current density when coexpressed with wild-type subunits[27]. The epilepsy phenotype might be related to the extent of mutation-induced functional $K_v2.1$

channel impairment, influenced by other genetic or environmental factors. No other phenotype-genotype correlations were found.

Epilepsy phenotypes associated with variants in other potassium channel genes show similar phenotypic heterogeneity, such as *KCNA2*, *KCNQ2*, *KCNQ3*, *KCNH1*, *KCNJ10*, *KCNT1*[28–33]. The underlying pathophysiological explanations for such pleiotropy remain largely unknown. For *KCNA2*, different functional effects of some variants have been associated with distinct epilepsy phenotypes[34]. However, a recent functional study of 17 *KCNB1* variants did not support such a correlation[27], consistent with the observation that recurrent missense variants cause a spectrum of phenotypes.

In addition to epilepsy and neurodevelopmental phenotypes, pathogenic variants in ion-channel genes have been associated with other central nervous system (CNS) and extra-CNS manifestations. Extra-CNS manifestations are thought to be related to the expression of these genes in different organs outside the CNS[35,36]. *KCNB1* encodes the α subunit of the voltage-gated potassium channel subfamily 2 (K_v2.1) which is widely expressed across the central nervous system but also in the heart, lung, liver, colon, kidney and adrenal gland[37]. Cardiac disorders and SUDEP have not yet been reported in individuals with *KCNB1* encephalopathy. Hypotonia was reported in half of the patients and likely has a central basis considering the strong expression of K_v2.1 in the cortex and its major role in regulating excitability in pyramidal neocortical neurons[38,39]. Although ataxia was reported in 20% of individuals, no evidence of cerebellar abnormality was seen on MRI nor signs of motor neuropathy on clinical examination.

Patient 6 had focal epilepsy, beginning at 4 years, with focal cortical dysplasia (Figure 4). She had the recurrent missense variant p.Arg306Cys, identified in three individuals (including patient 5) and none had focal cortical dysplasia[8,11]. Malformations of cortical development have been described in epilepsies due to ion-channel gene variants, including *SCN1A* and *KCNT1*[40,41]. However, the underlying pathogenesis of cortical malformation due to these genes remains unclear, especially as neuropathological data are scarce given the ongoing debate regarding the efficacy of epilepsy surgery in this population[42].

The retrospective nature of our study, without quantitative evaluation of neurodevelopment and ASD, is a limitation. Recruitment of most individuals occurred via tertiary epilepsy centres which may have led to an under-estimate of the prevalence of individuals with *KCNB1* DE without epilepsy. However, the frequency of *KCNB1* DE without epilepsy was higher in our series (6/36) than in published cases (3/37)[11].

We establish *KCNB1* as an important cause of DEE, early DE and DE and epilepsy. All are associated with a poor long-term cognitive, psychiatric and behavioral prognosis. Although frequent, epilepsy exhibits a wide phenotypic spectrum ranging from drug-resistant early-onset DEE to DE and pharmaco-responsive epilepsy. These findings highlight the urgent need to develop experimental models to gain insight to the underlying pathophysiological mechanisms of *KCNB1* encephalopathy and to develop targeted compounds that can ameliorate the neurodevelopmental outcome.

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Disclosure of Conflicts of Interest

Ingrid Scheffer serves/has served on the editorial boards of the Annals of Neurology, Neurology and Epileptic Disorders; may accrue future revenue on pending patent WO61/010176 (filed: 2008): Therapeutic Compound; has a patent for SCN1A testing held by Bionomics Inc and licensed to various diagnostic companies; she has a patent molecular diagnostic/theranostic target for benign familial infantile epilepsy (BFIE) [PRRT2] 2011904493 & 2012900190 and PCT/AU2012/001321 (TECH ID:2012-009) with royalties paid. She has served on scientific advisory boards for UCB, Eisai, GlaxoSmithKline, BioMarin, Nutricia, Rogcon and Xenon Pharmaceuticals; has received speaker honoraria from GlaxoSmithKline, UCB, BioMarin, Biocodex and Eisai; has received funding for travel from UCB, Biocodex, GlaxoSmithKline, Biomarin and Eisai; has consulted for UCB, Zynerba Pharmaceuticals and Ovid therapeutics. She receives/has received research support from the National Health and Medical Research Council of Australia, Health Research

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Ethical Publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

References

1. Bamshad MJ, Nickerson DA, Chong JX. Mendelian Gene Discovery: Fast and Furious with No End in Sight. Vol. 105, American Journal of Human Genetics. Cell Press; 2019. p. 448-55.

2. Scheffer IE, Berkovic S, Capovilla G, Connolly MB, French J, Guilhoto L, et al. ILAE classification ofthe epilepsies: Position paper ofthe ILAE Commission for Classification and Terminology. Epilepsia. 2017; 58(4):512-21.

3. Nabbout R, Dulac O. Epileptic encephalopathies: a brief overview. J Clin Neurophysiol Off Publ Am Electroencephalogr Soc. 2003; 20(6):393-7.

4. Wang J, Lin ZJ, Liu L, Xu HQ, Shi YW, Yi YH, et al. Epilepsy-associated genes. Vol. 44, Seizure. W.B. Saunders Ltd; 2017. p. 11-20.

5. McTague A, Howell KB, Cross JH, Kurian MA, Scheffer IE. The genetic landscape of the epileptic encephalopathies of infancy and childhood. Lancet Neurol. 2016; 15(3):304-16.

6. Hwang PM, Fotuhi M, Bredt DS, Cunningham AM, Snyder SH. Contrasting immunohistochemical localizations in rat brain of two novel K+ channels of the Shab subfamily. J Neurosci. 1993; 13(4):1569-76.

7. Torkamani A, Bersell K, Jorge BS, Bjork RL, Friedman JR, Bloss CS, et al. De novo KCNB1 mutations in epileptic encephalopathy. Ann Neurol. 2014; 76(4):529-40.

8. Saitsu H, Akita T, Tohyama J, Goldberg-Stern H, Kobayashi Y, Cohen R, et al. De novo KCNB1 mutations in infantile epilepsy inhibit repetitive neuronal firing. Sci Rep. 2015; 5.

9. Thiffault I, Speca DJ, Austin DC, Cobb MM, Eum KS, Safina NP, et al. A novel epileptic encephalopathy mutation in KCNB1 disrupts Kv2.1 ion selectivity, expression, and localization. J Gen Physiol. 2015; 146(5):399-410.

10. Calhoun JD, Vanoye CG, Kok F, George AL, Kearney JA. Characterization of a KCNB1 variant associated with autism, intellectual disability, and epilepsy . Neurol Genet. 2017; 3(6):e198.

11. De Kovel CGF, Syrbe S, Brilstra EH, Verbeek N, Kerr B, Dubbs H, et al. Neurodevelopmental disorders caused by de novo variants in KCNB1 genotypes and phenotypes. JAMA Neurol. 2017; 74(10):1228-36.

12. Latypova X, Matsumoto N, Vinceslas-Muller C, Bézieau S, Isidor B, Miyake N. Novel KCNB1 mutation associated with non-syndromic intellectual disability. J Hum Genet. 2017; 62(5):569-73.

13. Marini C, Romoli M, Parrini E, Costa C, Mei D, Mari F, et al. Clinical features and outcome of 6 new patients carrying de novo KCNB1 gene mutations . Neurol Genet. 2017; 3(6):e206.

14. Miao P, Feng J, Guo Y, Wang J, Xu X, Wang Y, et al. Genotype and phenotype analysis using an epilepsy-associated gene panel in Chinese pediatric epilepsy patients. Clin Genet. 2018; 94(6):512-20.

15. Samanta D. Epileptic spasm and de novo KCNB1 mutation: if it is not one potassium channel, it is another! Acta Neurol Belg. 2020; 120(2):417-20.

16. Bar C, Barcia G, Jennesson M, Le Guyader G, Schneider A, Mignot C, et al. Expanding the genetic and phenotypic relevance of KCNB1 variants in developmental and epileptic encephalopathies: 27 new patients and overview of the literature. Hum Mutat. 2020; 41(1):69-80.

17. Fisher RS, Cross JH, French JA, Higurashi N, Hirsch E, Jansen FE, et al. Operational classification of seizure types by the International League Against Epilepsy: Position Paper of the ILAE Commission for Classification and Terminology. Epilepsia. 2017; 58(4):522-30.

18. Richards S, Aziz N, Bale S, Bick D, Das S, Gastier-Foster J, et al. Standards and guidelines for the interpretation of sequence variants: A joint consensus recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology. Genet Med. 2015; 17(5):405-24.

19. den Dunnen JT, Dalgleish R, Maglott DR, Hart RK, Greenblatt MS, Mcgowan-Jordan J, et al. HGVS Recommendations for the Description of Sequence Variants: 2016 Update. Hum Mutat. 2016; 37(6):564-9.

20. Soden SE, Saunders CJ, Willig LK, Farrow EG, Smith LD, Petrikin JE, et al. Effectiveness of exome and genome sequencing guided by acuity of illness for diagnosis of neurodevelopmental disorders. Sci Transl Med. 2014; 6(265).

21. Fitzgerald TW, Gerety SS, Jones WD, Van Kogelenberg M, King DA, McRae J, et al. Large-scale discovery of novel genetic causes of developmental disorders. Vol. 519, Nature. Nature Publishing Group; 2015. p. 223-8.

22. Allen NM, Conroy J, Shahwan A, Lynch B, Correa RG, Pena SDJ, et al. Unexplained early onset epileptic encephalopathy: Exome screening and phenotype expansion. Epilepsia. 2016; 57(1):e12-7.

23. de Kovel CGF, Brilstra EH, Van Kempen MJA, Van't Slot R, Nijman IJ, Afawi Z, et al. Targeted sequencing of 351 candidate genes for epileptic encephalopathy in a large cohort of patients. Mol Genet Genomic Med. 2016; 4(5):568-80.

24. Parrini E, Marini C, Mei D, Galuppi A, Cellini E, Pucatti D, et al. Diagnostic Targeted Resequencing in 349 Patients with Drug-Resistant Pediatric Epilepsies Identifies Causative Mutations in 30 Different Genes. Hum Mutat. 2017; 38(2):216-25.

25. Schönewolf-Greulich B, Bisgaard AM, Møller RS, Dunø M, Brøndum-Nielsen K, Kaur S, et al. Clinician's guide to genes associated with Rett-like phenotypes—Investigation of a Danish cohort and review of the literature. Vol. 95, Clinical Genetics. Blackwell Publishing Ltd; 2019. p. 221-30.

26. Khajavi M, Inoue K, Lupski JR. Nonsense-mediated mRNA decay modulates clinical outcome of genetic disease. Eur J Hum Genet. 2006; 14(10):1074.

27. Kang SK, Vanoye CG, Misra SN, Echevarria DM, Calhoun JD, O'Connor JB, et al. Spectrum of KV2.1 Dysfunction in KCNB1-Associated Neurodevelopmental Disorders. Ann Neurol. 2019; 86(6):899-912.

28. Charlier C, Singh NA, Ryan SG, Lewis TB, Reus BE, Leach RJ, et al. A pore mutation in a novel KQT-like potassium channel gene in an idiopathic epilepsy family. Nat Genet. 1998; 18(1):53-5.

29. Singh NA, Charlier C, Stauffer D, DuPont BR, Leach RJ, Melis R, et al. A novel potassium channel gene, KCNQ2, is mutated in an inherited epilepsy of newborns. Vol. 18, Nature Genetics. Nat Genet; 1998. p. 25-9.

30. Sicca F, Imbrici P, D'Adamo MC, Moro F, Bonatti F, Brovedani P, et al. Autism with Seizures and Intellectual Disability: Possible Causative Role of Gain-of-function of the Inwardly-Rectifying K + Channel Kir4.1. Neurobiol Dis. 2011; 43(1):239-47.

31. Barcia G, Fleming MR, Deligniere A, Gazula V-R, Brown MR, Langouet M, et al. De novo gain-of-function KCNT1 channel mutations cause malignant migrating partial seizures of infancy. Nat Genet. 2012; 44(11):1255-9.

32. Simons C, Rash LD, Crawford J, Ma L, Cristofori-Armstrong B, Miller D, et al. Mutations in the voltage-gated potassium channel gene KCNH1 cause Temple-Baraitser syndrome and epilepsy. Nat Genet. 2015; 47(1):73-7.

33. Syrbe S, Hedrich UBS, Riesch E, Djémié T, Müller S, Møller RS, et al. De novo loss-or gain-of-function mutations in KCNA2 cause epileptic encephalopathy. Nat Genet. 2015; 47(4):393-9.

34. Masnada S, Hedrich UBS, Gardella E, Schubert J, Kaiwar C, Klee EW, et al. Clinical spectrum and genotype–phenotype associations of KCNA2-related encephalopathies. Brain. 2017; 140(9):2337-54.

35. Gitiaux C, Chemaly N, Quijano-Roy S, Barnerias C, Desguerre I, Hully M, et al. Motor neuropathy contributes to crouching in patients with Dravet syndrome. Neurology. 2016; 87(3):277-81.

36. Goldman AM, Behr ER, Semsarian C, Bagnall RD, Sisodiya S, Cooper PN. Sudden unexpected death in epilepsy genetics: Molecular diagnostics and prevention. In: Epilepsia. Blackwell Publishing Inc.; 2016. p. 17-25.

37. Schnitzler MM, Rinné S, Skrobek L, Renigunta V, Schlichthörl G, Derst C, et al. Mutation of histidine 105 in the T1 domain of the potassium channel Kv2.1 disrupts heteromerization with Kv6.3 and Kv6.4. J Biol Chem. 2009; 284(7):4695-704.

38. Bekkers JM. Distribution and activation of voltage-gated potassium channels in cell-attached and outside-out patches from large layer 5 cortical pyramidal neurons of the rat. J Physiol. 2000; 525(3):611-20.

39. Guan D, Tkatch T, Surmeier DJ, Armstrong WE, Foehring RC. Kv2 subunits underlie slowly inactivating potassium current in rat neocortical pyramidal neurons. J Physiol. 2007; 581(3):941-60.

40. Barba C, Parrini E, Coras R, Galuppi A, Craiu D, Kluger G, et al. Co-occurring malformations of cortical development and SCN1A gene mutations. Epilepsia. 2014; 55(7):1009-19.

41. Rubboli G, Plazzi G, Picard F, Nobili L, Hirsch E, Chelly J, et al. Mild malformations of cortical development in sleep-related hypermotor epilepsy due to KCNT1 mutations. Ann Clin Transl Neurol. 2019; 6(2):386-91.

42. Stevelink R, Sanders MWCB, Tuinman MP, Brilstra EH, Koeleman BPC, Jansen FE, et al. Epilepsy surgery for patients with genetic refractory epilepsy: a systematic review. Epileptic Disord. 2018; 20(2):99-115.

Table 1. Phenotypic spectrum of the 73 individuals from this series and published reports.

	Number of patients/patients with available data (%)

Median age at study in years (IQR)	9 (5-15)
Clinical examination	
Global or truncal hypotonia	32/62 (52)
Pyramidal signs (hypertonia with spasticity)	15/62 (24)
Ataxia	14/62 (23)
Dystonia, choreoathetosis	10/62 (16)
Hyperlaxity	9/62 (15)
Apraxia, dyspraxia	5/62 (8)
Motor milestones (individuals ≥ 2 years)	
Independent walking	36/50 (72)
Median age at walking in months (IQR)	24 (18-36)
Walk with support	4/50 (8)
Non ambulatory	10/50 (20)
Language development (individuals ≥ 3 years)	
Non-verbal	25/49 (51)
Single words	13/49 (27)
Speaks short sentences	11/49 (22)
Intellectual disability	
Mild	5/61 (8)
Moderate	15/61 (25)
Severe	39/61 (64)
Profound	2/61 (3)
Behavioral and psychiatric impairment	
Autistic features	32/57 (56)
Aggression	22/57 (39)
Impulsiveness/Hyperactivity	20/57 (35)
Epilepsy	
Patients with epilepsy	63/72 (88)
Median age at seizure onset in months (IQR)	13 (9-24)
Seizure types	
- Generalized onset seizures	50/61 (82)
Generalized tonic-clonic seizures	29/61 (48)
Generalized epileptic spasms	21/61 (34)
Generalized tonic seizures	18/61 (30)
Atypical absences	15/61 (25)
Generalized myoclonic seizures	15/61 (23)
Generalized atonic seizures	10/61 (16)
Generalized clonic seizures	4/61 (7)
Absence with eyelid myoclonic	1/61 (2)
- Focal onset seizures	30/61 (49)

Focal motor seizures	18/61 (30)
Focal non-motor seizures	13/61 (21)
- Seizures with unknown onset	7/61 (11)
Epilepsy syndromes	
- Unclassified DEE	23/45 (51)
- Infantile spasms	7/45 (16)
- Lennox-Gastaut syndrome	4/45 (9)
- Jeavons syndrome	1/45 (2)
- Unknown	10/45 (22)

DEE, developmental and epileptic encephalopathy; IQR, interquartile range.

Figure 1. Photographs of patients with *KCNB1* encephalopathy.

Note sunken eyes (A,C) and large median incisors (A,B,C,E,G,H).

Figure 2. Epilepsy phenotype of the 30 individuals with *KCNB1* encephalopathy and epilepsy, according to the International League Against Epilepsy (ILAE) classification.

Individuals with epilepsy were classified as having *KCNB1* DEE or *KCNB1* DE and epilepsy. Number of individuals with each seizure types and epilepsy types are indicated as well as the epilepsy syndromes for each group. Co-morbidities represent the neurodevelopmental phenotype of individuals with epilepsy. Data on ambulation and oral language are indicated for individuals older than 2 and 3 years, respectively.

ASD, autism spectrum disorder; DE, developmental encephalopathy; DEE, developmental and epileptic encephalopathy; ID, intellectual disability; LGS, Lennox-Gastaut syndrome; y, years.

Figure 3. Interictal EEG recordings of patients with *KCNB1* encephalopathy.

Interictal EEG recording of patient 28 with *KCNB1* DEE showing slowing of background activity with frequent diffuse spike-and-waves, predominant in anterior regions, during awake (A) and sleep (B) at 9 years. Interictal sleep EEG recording of patient 14 with *KCNB1* DEE showing abundant and multifocal paroxysmal activity at 4 years (C). Interictal sleep EEG recording of patient 16 with *KCNB1* DE showing normal background activity with sleep spindles and K-complexes at 12 months (D).

Figure 4. Brain magnetic resonance image (MRI) revealing 2 areas of focal cortical dysplasia in individual 6 with *KCNB1* encephalopathy and focal epilepsy.

Brain MRI of individual 6 performed at epilepsy onset at 4 years showing a right frontal cortical dysplasia with transmantle sign (arrow) and blurring on T1 inversion recovery coronal sequence (A) and Flair sequence (B) and a right temporo-parietal focal cortical dysplasia with transmantle sign (arrow) and blurring on T1 inversion recovery coronal sequence (C) and Flair sequence (D).

Figure 5. Distribution of phenotypes according to the type and position of *KCNB1* variant.

Phenotypic spectrum (*y*-axis) associated with each reported *KCNB1* variant is represented according to its amino-acid position and domain of the protein (*x*-axis). Stars and circles beside amino-acid position indicate frameshift and nonsense variants, respectively. Functional transmembrane domains of the protein are represented in grey (S1, S4, S5, pore helix, selectivity filter, S6) while extramembrane domains are represented in white columns (N-ter, S1-S2, S3-S4, S5-S6).

ASD, Autism spectrum disorder; C-ter, C-terminal domain; DE, developmental encephalopathy; DEE, developmental and epileptic encephalopathy; IS, infantile spasms; LGS, Lennox-Gastaut syndrome; NA, non-available; N-ter, N-terminal domain; S, segment.

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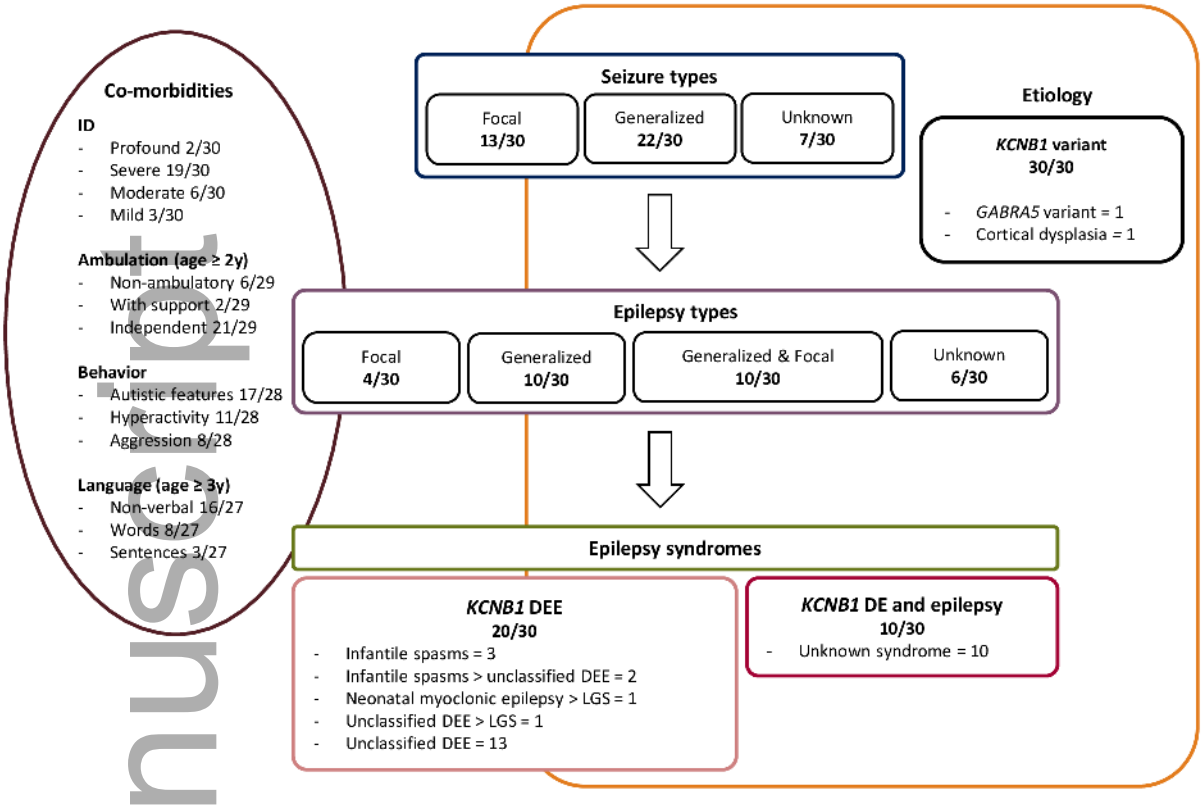

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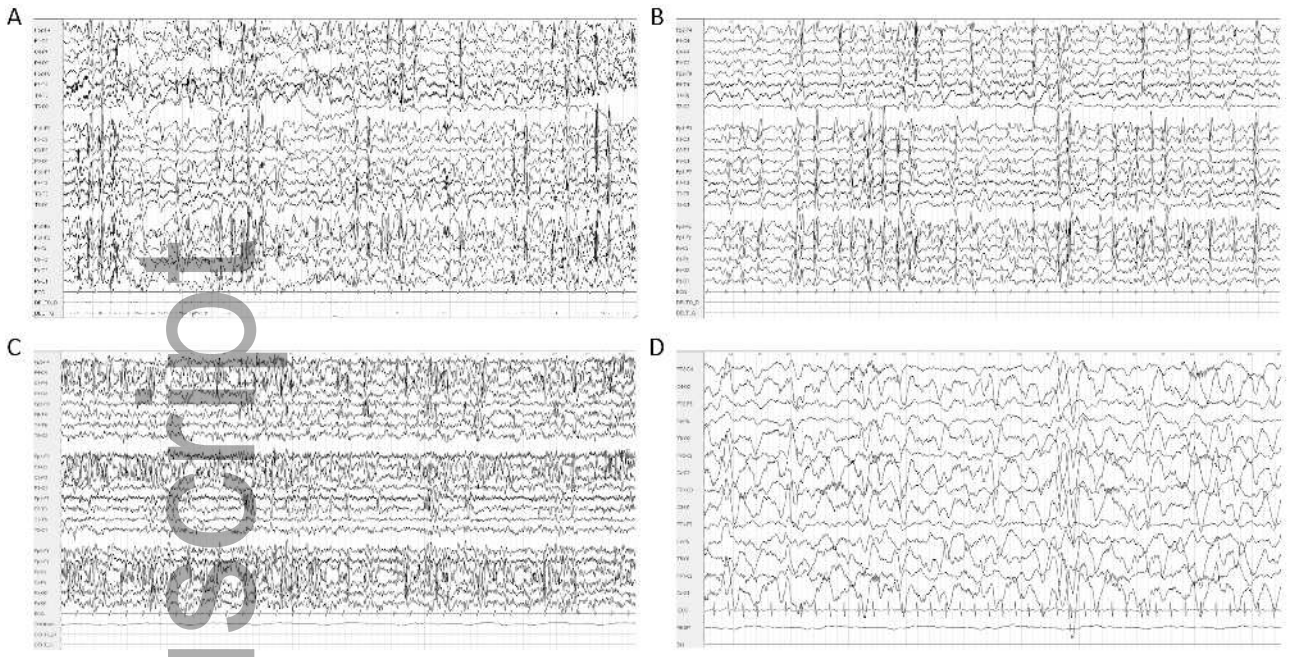

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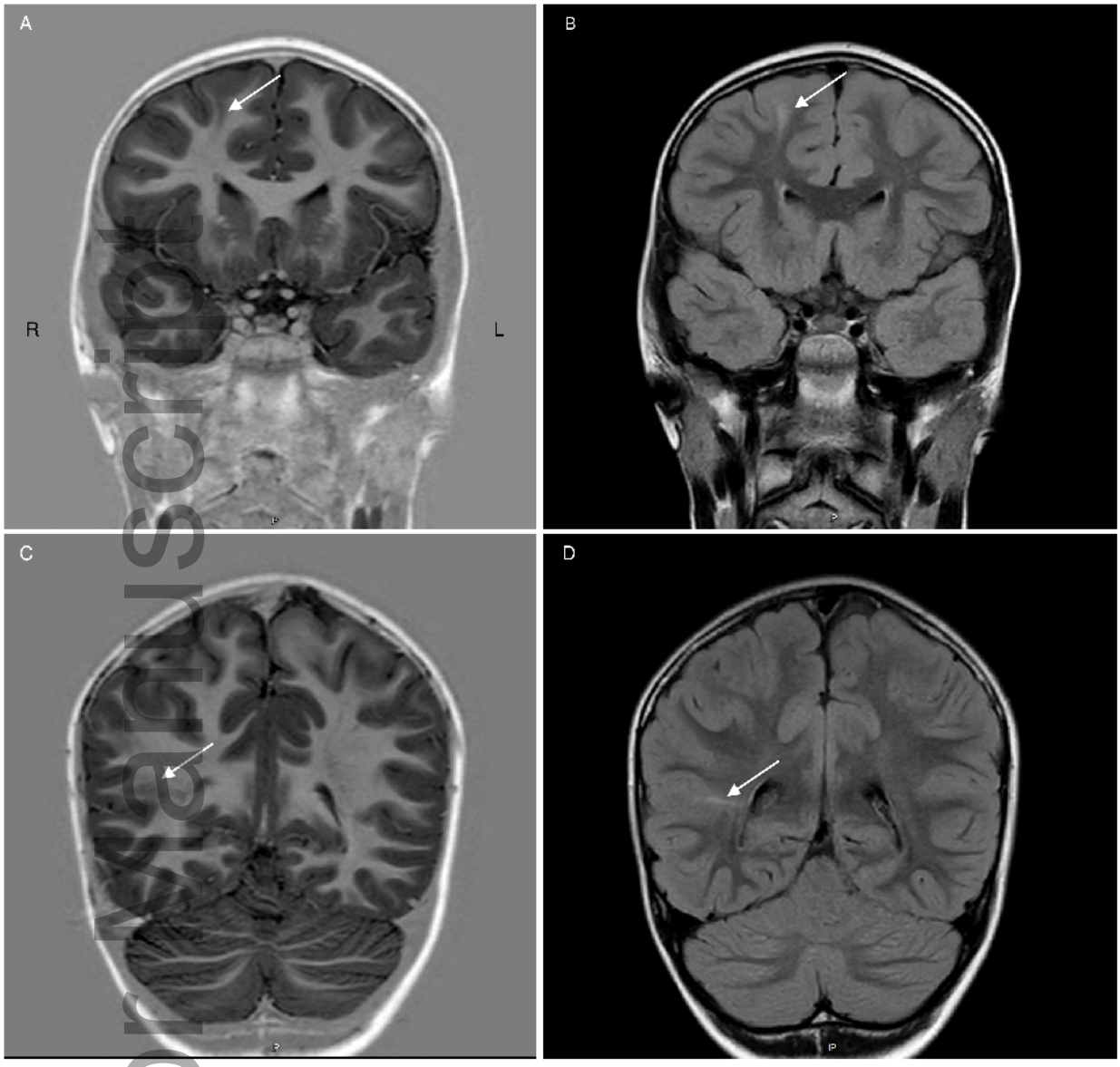

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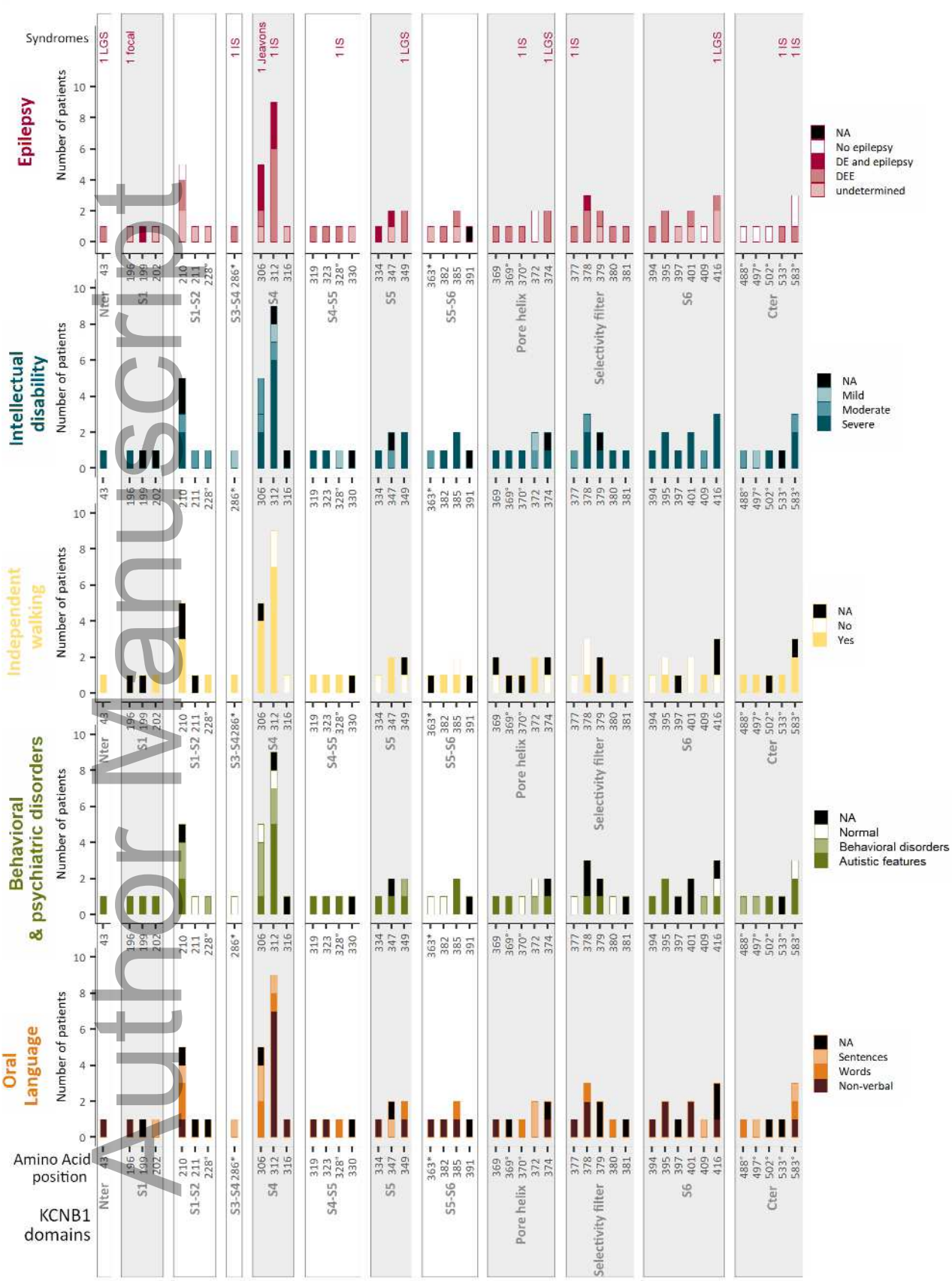

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