Remarkable effect of transdermal nicotine in children with *CHRNA4*-related autosomal dominant sleep-related hypermotor epilepsy

Kristine Lossius [a,1,2], Anne de Saint Martin [b,2], Sverre Myren-Svelstad [c,d,e,*], Marit Bjørnvold [a], Guro Minken [a], Caroline Seegmuller [b,f], Maria Paola Valenti Hirsch [f], Jamel Chelly [g], Ortrud Steinlein [h], Fabienne Picard [i], Eylert Brodtkorb [c,e]

[a] National Centre for Epilepsy, Division for Clinical Neuroscience, Oslo University Hospital, Oslo, Norway
[b] Pediatric Neurology, Reference Center for Rare Epilepsies, Strasbourg University Hospital, France
[c] Department of Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, Trondheim, Norway
[d] Kavli Institute for Systems Neuroscience and Centre for Neural Computation, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, Trondheim, Norway
[e] Department of Neurology and Clinical Neurophysiology, St. Olav University Hospital, Trondheim, Norway
[f] Neurology Department, Reference Center for Rare Epilepsies, Strasbourg University Hospital, France
[g] Genetic Department, Strasbourg University, Hospital, IGBMC, INSERM, CNRS, Strasbourg University, France
[h] Institute of Human Genetics, University Hospital, Ludwig Maximillian University of Munich, Munich, Germany
[i] EEG and Epilepsy Unit, Department of Neurology, University Hospitals and Medical School of Geneva, Geneva, Switzerland

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ABSTRACT

Objective: Autosomal dominant sleep-related hypermotor epilepsy (ADSHE) is characterized by hypermotor seizures and may be caused by gain-of-function mutations affecting the nicotinic acetylcholine receptor (nAChR). Benefit from nicotine consumption has been reported in adult patients with this disorder. For the first time, the effect of transdermal nicotine is evaluated in children.

Methods: Transdermal nicotine was applied to three boys, two aged 10 years (7 mg/24 h) and one six years (3.5 mg/24 h). Autosomal dominant sleep-related hypermotor epilepsy was caused by the p.S280F-*CHRNA4* (cholinergic receptor, nicotinic, alpha polypeptide 4) mutation. The children suffered from frequent, persistent nocturnal seizures and had developed educational and psychosocial problems. Seizure frequency and cognitive and behavioral parameters were assessed before and after treatment.

Results: A striking seizure reduction was reported soon after treatment onset. Hypermotor seizures disappeared; only sporadic arousals, sometimes with minor motor elements, were observed. Psychometric testing documented improvement in cognitive domains such as visuospatial ability, processing speed, memory, and some areas of executive functions.

Significance: Nicotine appears to be a mechanistic treatment for this specific disorder, probably because of desensitization of the mutated receptors. It may control seizures resistant to conventional drugs for epilepsy and impact socioeducational function in children. This mode of precision therapy should receive more attention and should be available to more patients with uncontrolled *CHRNA4*-related ADSHE across the age span.

1. Introduction

Autosomal dominant sleep-related hypermotor epilepsy (ADSHE) is characterized by clusters of hypermotor seizures arising from non-rapid eye movement (non-REM) sleep. The disorder was previously denoted autosomal dominant nocturnal frontal lobe epilepsy (ADNFLE) [1]. Autosomal dominant sleep-related hypermotor epilepsy follows an autosomal dominant inheritance with incomplete penetrance. The exact prevalence is unknown; the disorder is likely underdiagnosed, and some sporadic cases may also be of genetic origin [2].

Autosomal dominant sleep-related hypermotor epilepsy was the first seizure disorder with a proven monogenic origin [3]. Many

monogenic epilepsies are channelopathies as they are related to genes encoding for ion channels gated by voltage or a neurotransmitter [4]. Several genes associated with ADSHE code for subunits of the nicotinic acetylcholine receptors (nAChRs), which are ion channels gated by acetylcholine and nicotine [5,6]. The most common mutations occur in the CHRNA4 (cholinergic receptor, nicotinic, alpha polypeptide 4) gene, encoding the alpha4 subunit that interacts with various combinations of alpha and beta subunits to form functional nAChRs [5,7,8].

Even though carbamazepine and other antiepileptic drugs (AEDs) are effective in many patients with ADSHE, a large proportion of those carrying the p.S280F-CHRNA4 mutation (previously designated S248F) continue to have seizures [3,8–10]. Treatment with transdermal nicotine appears to be beneficial in some patients with this disorder as first reported in a single Australian patient with this mutation [11]. In two Norwegian pedigrees with p.S280F mutations and p.L291dup-CHRNA4 mutations (previously 776ins3), respectively, seizure control was significantly associated with tobacco consumption [12].

Although nicotine consumption is common as self-medication among patients with ADSHE due to CHRNA4 mutations, the literature on this form of precision therapy has been sparse [12,13]. Because of concerns about the safety profile, nicotine substitution has as yet only been suggested for treatment of adult patients with insufficient effect of established AEDs. However, in underaged patients with severe and intractable ADSHE due to nAChR mutations, targeted treatment with nicotine may also be considered.

For the first time, the effect of transdermal nicotine in children with ADSHE due to the p.S280F-CHRNA4 mutation is reported. We evaluated the impact both on seizure control and on cognitive performance.

Ethical approval other than written informed consent from the parents of these children was not required by the Regional Committees for Medical and Health Research Ethics.

2. Clinical pictures and treatment response

An overview of clinical characteristics and the effect of transdermal nicotine in the three children is given in Tables 1–3.

2.1. Case 1

This 14 years old Norwegian boy was born after an uneventful pregnancy and had a normal development prior to seizure onset. His mother was treated for uncontrolled ADSHE with continued carbamazepine and topiramate during gestation.

The first nocturnal seizures were recognized at three years of age. The attacks gradually became more prominent, and he had seizures every night that were described as arousals from sleep with hypermotor mping, rocking, dystonic jerks, guttural sounds, and vocalization), often in series, usually lasting <1 min.

Standard awake electroencephalograms (EEGs) were normal. Nocturnal video-EEG showed multiple hypermotor attacks with electrographic signs of arousal during non-REM sleep but no ictal epileptic activity.

At the age of five, he started treatment with oxcarbazepine with only minor benefit. The dose was increased, but by the age of six, he still experienced seizures almost every night. At the age of seven, his attention-deficit hyperactivity disorder (ADHD) was diagnosed. Despite treatment with methylphenidate, he had learning and behavioral difficulties. By the age of nine, he also developed tics suggestive of Tourette syndrome and a tendency to obsessive–compulsive behavior. He followed normal class with special educational support.

At the age of 10, his parents reported multiple hypermotor seizures every night, sometimes even seizures suspected to be bilateral tonic–clonic. Neuropsychological testing, including Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV), showed a general performance at low-average level. He particularly struggled with working memory and processing speed and showed severe attention and executive difficulties.

Video-monitoring during several nights at the National Centre for Epilepsy showed 2–30 hypermotor seizures every night. One-night video-EEG recording demonstrated approximately 30 stereotypical events with truncal and limb stiffening, partly with brusque sitting-up, sometimes with head deviation and body turning to the right. They lasted for about 30–40 s without corresponding ictal EEG activity, only signs of arousal.

He tried lamotrigine combined with oxcarbazepine without effect. He started treatment with transdermal nicotine 7 mg/24 h (approximately 0.12 mg/kg/24 h) as add-on to oxcarbazepine. During the first days, the parents reported a tendency to more severe seizures followed by a striking improvement. He complained of headache on the first evening of treatment, but subsequently, no adverse effects were reported. The parents reported a remarkable improvement with only rare and

Table 2
Effect of transdermal nicotine on seizure outcome in three children with p.S280F-CHRNA4-related epilepsy.

	Before nicotine treatment	On nicotine treatment
Case 1	2–30 hypermotor seizures/night	Rare paroxysmal arousals
Case 2	Up to 10 hypermotor seizures/night	Rare paroxysmal arousals, sometimes with subtle motor elements
Case 3	>20 hypermotor seizures/night	0–3 subtle motor seizures/week

Table 1
Characteristics of p.S280F-CHRNA4-related epilepsy in three children.

	Case 1	Case 2	Case 3
Current age	14 years	8 years, 2 months	11 years, 10 months
Age at seizure onset	3 years	2 years	5 years
Age at onset of nicotine treatment	10 years, 11 months	6 years, 2 months	10 years, 7 months
Seizures	Hypermotor/asymmetric tonic posturing/paroxysmal arousals	Hypermotor/asymmetric tonic posturing/paroxysmal arousals	Hypermotor/asymmetric tonic posturing/limb dystonia, paroxysmal arousals
Brain magnetic resonance imaging (MRI)	Normal (1.5 T)	Normal (1.5 T)	Normal (3 T)
Interictal EEG (awake and sleep)	Normal, apart from centrofrontal sharp activity during non-REM sleep at one occasion	Normal	Normal, apart from left frontal spike-waves during sleep at first recording
Ictal EEG	Arousal pattern; no epileptiform activity	Arousal pattern; no epileptiform activity, apart from suspect bifrontal rhythmic sharp activity at two occasions	Rhythmic polyspikes, and left frontal theta activity or right central theta activity
Antiepileptic drugs tried	Oxcarbazepine, lamotrigine	Lamotrigine, oxcarbazepine	Valproate, lamotrigine, levetiracetam, topiramate, oxcarbazepine, zonisamide, carbamazepine

Table 3
Cognitive domain performance levels in three children with p.S280F-CHRNA4-related epilepsy before and during transdermal nicotine treatment.

	Cognitive domains	Before nicotine treatment	On nicotine treatment
Case 1	Processing speed	Below average to average	Low average to average
	Memory functions	Below average (verbal)	Average (verbal)
		Average (figurative)	
	Verbal/nonverbal reasoning	Low average (verbal)	Low average to average (verbal)
		Low average to average (nonverbal)	Low average to average (nonverbal)
	Executive functions	Below average to average	Below average to average
Case 2	Processing speed	Average	Low average to average
	Verbal/nonverbal reasoning	Low average (verbal)	Average (verbal)
		Low average (nonverbal)	Low average to average (nonverbal)
	Executive functions	Low average	Below average to average
Case 3	Processing speed	Average	Low average to average
	Memory functions	Low average	Average
	Verbal/nonverbal reasoning	Average (verbal)	Average (verbal)
		Below average (nonverbal)	Average (nonverbal)
	Executive functions	Below average	Below to low average

Cognitive domain performance levels are predominantly based on relevant subtests from the Wechsler Intelligence Scale for Children (WISC), versions IV or V; The Wechsler Preschool and Primary Scale of Intelligence (WPPSI), version IV; A Developmental NEuroPSYchological Assessment (NEPSY), second version; the Delis–Kaplan Executive Function System (D-KEFS); EpiTrack Junior; and Behavior Rating Inventory of Executive Function (BRIEF).
Performance level is related to average performance range in the reference group (below average = 2 or more standard deviation (SD) below average; low average = 1–2 SD below an average value, average = 1 SD or less below or above average; high average = 1–2 SDs above average score; and above average = 2 SDs or more above average score).

subtle motor symptoms. Seven months after treatment onset, video-EEG for two nights showed just a few uncharacteristic arousals. After two years, he stopped treatment with oxcarbazepine and continued with transdermal nicotine along with methylphenidate. Hypermotor seizures did not recur; he remained with rare episodes of restless sleep and occasional short-lasting awakenings after stressful events and lack of sleep (Table 2).

Following seizure control, improvement in daily function, learning, and behavior was reported. Neuropsychological retesting after six months demonstrated better scores especially for processing speed, working memory, and task switching. He also showed some improvement in verbal and nonverbal reasoning. At the age of 12 years, he was screened with EpiTrack Junior [14] with a total result within average range. However, supplementary testing and parents' report still showed difficulties regarding attention, impulsivity, working memory, and executive functions (Table 3).

2.2. Case 2

This boy aged eight years, brother of case 1, had a similar history. Early development was considered normal prior to seizure onset. Maternal treatment with carbamazepine and topiramate had been continued also through this pregnancy.

Seizures were suspected already from the age of two years. He developed the same seizure semiology as his brother. Language testing at the age of three years confirmed language delay, in particular impressive language.

Whole-night sleep video-EEG recordings at the age of four and six years showed multiple stereotypical paroxysmal arousals and hypermotor seizures without corresponding ictal EEG activity, similar to his brother (Table 2). Abrupt jerking and stiffening were sometimes accompanied by vocalization.

He also had a tendency to hyperactivity, impulsivity, and inattention. Neuropsychological testing at six years, including Wechsler Preschool and Primary Scale of Intelligence - Fourth Edition (WPPSI-IV), showed a general performance at low-average level for his age.

Treatment with lamotrigine had dubious benefit on seizure control and behavioral adverse effects. Oxcarbazepine was discontinued because of nausea after a few weeks. The hypermotor seizures disappeared with transdermal nicotine 3.5 mg/24 h (approximately 0.15 mg/kg/24 h). After six months, 24-h video-EEG recording was normal with no clinical signs of nocturnal seizure activity. In particular circumstances, such as febrile illness and after stressful events, he may have rare, subtle seizures with awakenings and minimal motor

elements. At eight years, such symptoms were associated with suspect ictal EEG activity in the form of bifrontal rhythmic sharp waves. Currently, the exposure to nicotine appears to be variable as he has a tendency to scratch off the patch because of itching during daytime. He remains with a tendency to impulsive and hyperactive behavior.

Neuropsychological testing at the age of eight years showed a low-average ability level with no significant change compared with the testing before nicotine treatment. However, the results indicated improvement in verbal and nonverbal reasoning with scores classified as average. Fine motor speed was impaired, and verbal learning and memory tests indicated deficits. Although some scores on tests of executive functions were considered normal, his parents reported problems consistent with severe executive dysfunction.

After application to the Norwegian Health Economics Administration, transdermal nicotine has been accepted for reimbursement for this specific disorder in the two Norwegian siblings.

2.3. Case 3

This French boy was born after an uneventful pregnancy. Early developmental milestones were normally achieved. His parents and his older brother are healthy.

At the age of five years, hypermotor seizures occurred during sleep. The first video-EEG recorded a motor seizure with right limb dystonia accompanied by left frontal delta activity. Interictal EEG showed left frontal spike-and-waves. Valproate and lamotrigine were ineffective. Levetiracetam and topiramate induced adverse effects, but he had some effect from carbamazepine.

Repeated nocturnal video-EEGs recorded 10 to 30 motor seizures/night with right limb dystonia, sometimes extended to both limbs and associated with frontal polyspikes, and interictal left frontal slow activity. Some seizures were more subtle arousals with eye opening and mild tonic posturing accompanied by bifrontal polyspikes.

Progressive behavioral deterioration with hyperactivity and attention-deficit held him back at school. Psychometric testing at seven years showed a working memory deficit but normal verbal and visual processing. Neuropsychological testing confirmed severe executive problems.

An intracerebral EEG recording (stereo-EEG) at the age of eight showed a widespread epileptogenic network, which excluded resective surgery. Despite additional drug trials with oxcarbazepine and zonisamide, the epilepsy worsened with more than 20 seizures/night. At the age of nine, the behavior deteriorated with anxiety and impulsiveness. His condition was treated with risperidone, and he received

special education. Psychometric testing showed worsening of the visual processing index (VPI) and the working memory index (WMI).

Transdermal nicotine 7 mg/24 h was introduced at the age of 10 years, while he was treated with carbamazepine and oxcarbazepine. Dramatic improvement with rapid decrease of seizure frequency was reported, together with a reduction of impulsiveness and anxiety. Nocturnal video-EEG recordings were performed two days before nicotine introduction and two months afterwards. The frequency of seizures had decreased by >70%, from 50 seizures/night with hypermotor elements to eight seizures/night with only arousals and mild posturing. Neuropsychological and psychometric testing performed four months after nicotine introduction evidenced an improvement in control and attention and a normalization of VPI. Executive functioning was still impaired, but improvement was observed for verbal fluency and memory tests. The Child Behavior Checklist (CBCL) had also improved.

One year after introduction of transdermal nicotine, the boy is able to attend secondary school with educational support. Antiepileptic drug treatment has been reduced to carbamazepine monotherapy, and risperidone was lowered. Nicotine treatment is well tolerated. The parents only observe seizures very occasionally during stressful periods. They report a better daily social functioning. The CBCL score remains abnormal, and neuropsychological testing still shows impulsiveness and executive deficits one year after onset of nicotine treatment.

Written informed consent for participation in the study was provided from the parents of the three children.

3. Inheritance

3.1. Cases 1 and 2

These brothers belong to a large Norwegian family with ADSHE caused by the p.S280F-CHRNA4 variant (c.839C>T). Both boys and their mother carry the mutation. Genetic testing was limited to analysis for the present mutation. Clinical and genetic characteristics of the pedigree were already reported prior to the birth of these children [8].

3.2. Case 3

This French boy also carries the heterozygous p.S280F-CHRNA4 mutation, revealed by next-generation sequencing using a large epilepsy panel. He was first considered to be a sporadic case, but both his father and brother were shown to carry the same mutation. At a detailed interview, the father recalled recurrent 'nightmares' during childhood but had never been aware of hypermotor seizures. His wife had not observed nocturnal attacks. His older brother did neither experience arousals nor hypermotor seizures and had a normal cognitive function. This case illustrates the incomplete clinical penetrance and the high intrafamilial phenotypic heterogeneity of this mutation.

There is no known relationship between the Norwegian and the French family.

4. Discussion

Transdermal nicotine is established as an experimental therapy in adults with ADSHE due to CHRNA4 mutations. The novelty of this contribution is the young age of the patients and the impact of treatment on cognitive development. Our case series suggests that nicotine treatment may be safe and efficacious also in children.

4.1. Seizure control

In the three present boys with p.S280F-CHRNA4 mutations and multiple nocturnal seizures, there was an impressive effect on seizure frequency and severity, which is in line with previous reports in adults [11,12]. Two of the children stopped AED treatment because of side effects and maintained seizure control with nicotine monotherapy,

whereas the third child continued with concomitant carbamazepine. With unchanged treatment, the effect remained stable after a follow-up time of one to three years although poor adherence to the patch administration appeared to be associated with restless sleep and subtle attacks in the youngest Norwegian boy.

4.2. Encephalopathic features

Mutations in the nAChRs may have wider consequences than just the seizure disorder. Cognitive impairment involving executive and memory functions has been demonstrated among adult patients with ADSHE, including patients with the p.S280F-CHRNA4 mutation [8,15,16]. It has been suggested that these cognitive dysfunctions predominantly are due to the central nervous cholinergic abnormality [17]. The findings highlight the discussion on the differentiation between a 'developmental encephalopathy' and an 'epileptic encephalopathy', in which the epileptic activity itself contributes to neuropsychological impairment [18]. In two of the children, behavioral problems decreased after the introduction of nicotine, whereas cognitive impairment slightly improved in all. The present findings cannot determine whether nicotine exposure directly improves the cognitive and behavioral dysfunction or if seizure control itself and abolished ictal sleep fragmentation are crucial factors [16]. If the latter is true, intense antiseizure treatment might have the potential to reduce the overall clinical consequences of the disorder, corroborating the importance of early nicotine treatment in children with uncontrolled epilepsy. Moreover, this precision therapy may allow for a reduced adverse effect burden from AEDs.

An intriguing, yet hypothetical question is whether early nicotine treatment even can interact with brain development. A study based on positron emission tomography (PET) showed that patients with ADSHE had a higher density of nAChR in the brainstem along with decreased density in the forebrain compared with controls [17]. These findings challenged the channelopathy concept as they may suggest an architectural abnormality, conceivably acquired during brain development, although an alternative hypothesis is an upregulation of the gain-of-function mutated receptors in a region known to have a particularly high receptor density. In cases 1 and 2, an additional environmental effect on neurodevelopment from the fetal exposure to AEDs cannot be excluded [19]. Also, genetic complexity may influence comorbidity profiles in seizure disorders thought to be purely monogenic [20,21].

4.3. Pathophysiological considerations

Conceivably, the seizure reducing effect of nicotine relates to the pathophysiology of nAChR mutations. Typically, an increased acetylcholine sensitivity is observed in vitro in this form of ADSHE, hence, gain-of-function of nAChR appears to be the underlying mechanism [22,23]. The main hypotheses postulate that the mutated receptors cause altered γ-aminobutyric acid (GABA)-ergic interneuron activity leading to seizure generation [24]. It has been suggested that desensitization of the mutated receptors, 'normalizing' the receptor physiology, explains the effect of nicotine in ADSHE [12]. We postulate that nicotine may have a potential beneficial effect not only in patients with p.S280F-CHRNA4 mutations but in most patients with nAChR mutations as an increased sensitivity to acetylcholine has been identified in most functionally characterized mutations [24,25]. In one single adult patient with uncontrolled epilepsy carrying the p.S284L-CHRNA4 mutation, transdermal nicotine also provided seizure control [26]. A study in adults has also suggested benefit from nicotine in patients with the p.L291dup-CHRNA4 mutation [12]. However, electrophysiological studies have demonstrated major differences regarding the sensitivity to nicotine in various nAChR mutations, suggesting variations in pharmacogenomic properties not readily correlating with increased acetylcholine affinity [25]. Therefore, it is currently not possible to predict which patients will benefit from nicotine intervention; even a worsening effect cannot

be excluded in some mutations. Nicotine treatment should be initiated with care. More studies are needed to elucidate these issues further in relevant mutations, but clinical experience speaks for itself.

4.4. Risks of nicotine treatment

The safety of continuous nicotine exposure in children is obscure. Long-term health effects of nicotine itself are difficult to estimate as nicotine replacement therapy typically is used by previously heavy smokers [27]. However, there are concerns about hemodynamic effects of nicotine, which may have implications for risk of cardiovascular disease. Smokeless tobacco consumption in the form of snuffing ('snus') is widely used in the Scandinavian countries, even in the absence of former smoking. Swedish studies did neither find an association with ischemic heart disease [28] nor with stroke [29]. Nevertheless, future epidemiological studies should be kept under surveillance, and the balance between benefit and risk should be carefully weighed.

4.5. Nicotine treatment in ADSHE

Importantly, only a minority of patients with sleep-related hypermotor epilepsy (SHE) have mutations in nAChRs. Most cases are considered 'sporadic' without a clear family history [1,13]. Moreover, some patients have mutations in the sodium-activated potassium channel encoded by *KCNT1* (potassium channel subfamily T member 1) [30] in the *DEPDC5* (DEP domain containing 5, GATOR1 subcomplex unit) gene which encodes a repressor of the mammalian target of rapamycin (mTOR) pathway [31] and in the *CABP4* (Ca^{2+} binding protein 4) gene encoding the neuronal CaBP4 [32]. Interestingly, transdermal nicotine led to a complete resolution of the seizures in an adolescent with severe nonstructural frontal lobe epilepsy in the absence of *CHRNA4* or *CHRNB2* (cholinergic receptor, nicotinic, beta polypeptide 2) mutations [33], suggesting a similar mechanistic pathway in this patient. However, a case–control family study on sporadic cases of SHE did not show a significantly higher tendency to tobacco consumption in patients compared with controls [34]. Only empirical and anecdotal data yet support the efficacy of transdermal nicotine in ADSHE due to nAChR mutations. In this study, the number of treated patients was low, and the follow-up time was short. From the outset, this study was retrospective; various neuropsychological tests were applied at different points in time, and we could not consider the natural course or inherent fluctuations of the disorder in each individual. Unfortunately, the rarity of the disorder limits the opportunity to perform controlled trials in a large number of patients. Complete and reliable seizure diaries are usually impossible to obtain for sleep-related hypermotor seizures. Notwithstanding, we believe that the currently available clinical experience is sufficiently convincing to suggest that nicotine may be a mechanistic therapy in this specific type of seizure disorder as opposed to the symptomatic treatments used for most epilepsies. The effect on seizure control was remarkable in this series. For the first time, we have been able to demonstrate that cognitive and behavioral function also may improve, suggesting that this treatment approach may reduce the educational and psychosocial consequences of the disorder in young children. Children with SHE without known cause should all be tested for nAChR mutations.

5. Conclusion

Nicotine treatment for AED-resistant ADSHE should receive more attention as it may control seizures resistant to conventional AEDs and impact socioeducational function in children. This potential precision therapy should be available to more patients across the age span after a careful genetic and clinical selection as well as a thorough risk/benefit assessment. When prudently tried and effective, this mode of treatment should be reimbursed for this specific disorder by health authorities and medical insurance programs in line with standard AEDs.

References

[1] Tinuper P, Bisulli F, Cross JH, Hesdorffer D, Kahane P, Nobili L, et al. Definition and diagnostic criteria of sleep-related hypermotor epilepsy. Neurology 2016;86: 1834–42.
[2] Phillips HA, Marini C, Scheffer IE, Sutherland GR, Mulley JC, Berkovic SF. A de novo mutation in sporadic nocturnal frontal lobe epilepsy. Ann Neurol 2000; 48:264–7.
[3] Steinlein OK, Mulley JC, Propping P, Wallace RH, Phillips HA, Sutherland GR, et al. A missense mutation in the neuronal nicotinic acetylcholine receptor α4 subunit is associated with autosomal dominant nocturnal frontal lobe epilepsy. Nat Genet 1995; 11:201–3.
[4] Jones D, M JO. The epilepsies: phenotypes and mechanisms. In: Brady S, Siegel G, Albers R, Price D, editors. Basic neurochemistry. 8th ed. Elsevier; 2012. p. 705–18.
[5] Kurahashi H, Hirose S. Autosomal dominant nocturnal frontal lobe epilepsy. Gene reviews. Seattle (WA): University of Washington; 2002.
[6] Fisher S, Wonnacott S. Acetylcholine. In: Brady S, Siegel G, Albers R, Price D, editors. Basic neurochemistry. 8th ed. Oxford: Elsevier; 2012. p. 258–82.
[7] Steinlein OK, Magnusson A, Stoodt J, Bertrand S, Weiland S, Berkovic SF, et al. An insertion mutation of the CHRNA4 gene in a family with autosomal dominant nocturnal frontal lobe epilepsy. Hum Mol Genet 1997;6:943–7.
[8] Steinlein OK, Stoodt J, Mulley J, Berkovic S, Scheffer IE, Brodtkorb E. Independent occurrence of the CHRNA4 Ser248Phe mutation in a Norwegian family with nocturnal frontal lobe epilepsy. Epilepsia 2000;41:529–35.
[9] Scheffer IE, Bhatia KP, Lopes-Cendes I, Fish DR, Marsden CD, Andermann E, et al. Autosomal dominant nocturnal frontal lobe epilepsy: a distinctive clinical disorder. Brain 1995;118:61–73.
[10] Licchetta L, Bisulli F, Vignatelli L, Zenesini C, Di Vito L, Mostacci B, et al. Sleep-related hypermotor epilepsy: long-term outcome in a large cohort. Neurology 2017;88: 70–7.
[11] Willoughby JO, Pope KJ, Eaton V. Nicotine as an antiepileptic agent in ADNFLE: an N-of-one study. Epilepsia 2003;44:1238–40.
[12] Brodtkorb E, Picard F. Tobacco habits modulate autosomal dominant nocturnal frontal lobe epilepsy. Epilepsy Behav 2006;9:515–20.
[13] Menghi V, Bisulli F, Tinuper P, Nobili L. Sleep-related hypermotor epilepsy: prevalence, impact and management strategies. Nat Sci Sleep 2018;10:317–26.
[14] Helmstaedter C, Schoof K, Rossmann T, Reuner G, Karlmeier A, Kurlemann G. Introduction and first validation of EpiTrack Junior, a screening tool for the assessment of cognitive side effects of antiepileptic medication on attention and executive functions in children and adolescents with epilepsy. Epilepsy Behav 2010;19:55–64.
[15] Picard F, Pegna AJ, Arntsberg V, Lucas N, Kaczmarek I, Todica O, et al. Neuropsychological disturbances in frontal lobe epilepsy due to mutated nicotinic receptors. Epilepsy Behav 2009;14:354–9.
[16] Licchetta L, Poda R, Vignatelli L, Pippucci T, Zenesini C, Menghi V, et al. Profile of neuropsychological impairment in sleep-related hypermotor epilepsy. Sleep Med 2018; 48:8–15.
[17] Picard F, Bruel D, Servent D, Saba W, Fruchart-Gaillard C, Schollhorn-Peyronneau MA, et al. Alteration of the in vivo nicotinic receptor density in ADNFLE patients: a PET study. Brain 2006;129:2047–60.
[18] Scheffer IE, Berkovic S, Capovilla G, Connolly MB, French J, Guilhoto L, et al. ILAE classification of the epilepsies: position paper of the ILAE Commission for Classification and Terminology. Epilepsia 2017;58:512–21.
[19] Kellogg M, Meador KJ. Neurodevelopmental effects of antiepileptic drugs. Neurochem Res 2017;42:2065–70.
[20] Takata A, Nakashima M, Saitsu H, Mizuguchi T, Mitsuhashi S, Takahashi Y, et al. Comprehensive analysis of coding variants highlights genetic complexity in developmental and epileptic encephalopathy. Nat Commun 2019;10:2506.
[21] Scheffer IE, Liao J. When monogenic isn't monogenic—unravelling the oligogenic architecture of the developmental and epileptic encephalopathies. Epilepsy Curr 2019; 19:417–9.
[22] Moulard B, Picard F, le Hellard S, Agulhon C, Weiland S, Favre I, et al. Ion channel variation causes epilepsies. Brain Res Brain Res Rev 2001;36:275–84.
[23] Bertrand D. Neuronal nicotinic acetylcholine receptors and epilepsy. Epilepsy Curr 2002;2:191–3.

[24] Steinlein OK, Kaneko S, Hirose S. Nicotinic acetylcholine receptor mutations. In: Noebels JL, Avoli M, Rogawski MA, Olsen RW, Delgado-Escueta AV, editors. Jasper's basic mechanisms of the epilepsies. Bethesda (MD): National Center for Biotechnology Information (US); 2012.

[25] Hoda J, Gu W, Friedli M, Phillips H, Bertrand S, Antonarakis S, et al. Human nocturnal frontal lobe epilepsy: pharmocogenomic profiles of pathogenic nicotinic acetylcholine receptor beta-subunit mutations outside the ion channel pore. Mol Pharmacol 2008;2008:379–91.

[26] Pavlakis PP, Douglass LM. Pearls & Oy-sters: a case of refractory nocturnal seizures putting out fires without smoke. Neurology 2015;84:e134–6.

[27] Apelberg BJ, Onicescu G, Avila-Tang E, Samet JM. Estimating the risks and benefits of nicotine replacement therapy for smoking cessation in the United States. Am J Public Health 2010;100:341–8.

[28] Hansson J, Galanti MR, Hergens M-P, Fredlund P, Ahlbom A, Alfredsson L, et al. Use of snus and acute myocardial infarction: pooled analysis of eight prospective observational studies. Eur J Epidemiol 2012;27:771–9.

[29] Hansson J, Galanti MR, Hergens MP, Fredlund P, Ahlbom A, Alfredsson L, et al. Snus (Swedish smokeless tobacco) use and risk of stroke: pooled analyses of incidence and survival. J Intern Med 2014;276:87–95.

[30] Heron S, Smith K, Bahlo M, Nobili L, Kahana E, Licchetta L, et al. Missense mutations in the sodium-gated potassium channel gene KCNT1 cause severe autosomal dominant nocturnal frontal lobe epilepsy. Nat Genet 2012;44:1188–90.

[31] Dibbens L, de Vries B, Donatello S, Heron S, Hodgson B, Chintawar S, et al. Mutations in DEPDC5 cause familial focal epilepsy with variable foci. Nat Genet 2013;45: 546–51.

[32] Chen ZH, Wang C, Zhuo MQ, Zhai QX, Chen Q, Guo YX, et al. Exome sequencing identified a novel missense mutation c.464G>A (p.G155D) in Ca(2+)-binding protein 4 (CABP4) in a Chinese pedigree with autosomal dominant nocturnal frontal lobe epilepsy. Oncotarget 2017;8:78940–7.

[33] Zerem A, Nishri D, Yosef Y, Blumkin L, Lev D, Leshinsky-Silver E, et al. Resolution of epileptic encephalopathy following treatment with transdermal nicotine. Epilepsia 2013;54:e13–5.

[34] Naldi I, Bisulli F, Vignatelli L, Licchetta L, Pittau F, Di Vito L, et al. Tobacco habits in nocturnal frontal lobe epilepsy. Epilepsy Behav 2013;26:114–7.