Novel mutations in human and mouse SCN4A implicate AMPK in myotonia and periodic paralysis

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Mutations in the skeletal muscle channel (SCN4A), encoding the Na+,1.4 voltage-gated sodium channel, are causative of a variety of muscle channelopathies, including non-dystrophic myotonias and periodic paralysis. The effects of many of these mutations on channel function have been characterized both in vitro and in vivo. However, little is known about the consequences of SCN4A mutations downstream from their impact on the electrophysiology of the Na+,1.4 channel. Here we report the discovery of a novel SCN4A mutation (c.1762A > G; p.I588V) in a patient with myotonia and periodic paralysis, located within the S1 segment of the second domain of the Na+,1.4 channel. Using N-ethyl-N-nitrosourea mutagenesis, we generated and characterized a mouse model (named draggen), carrying the equivalent point mutation (c.1744A > G; p.I582V) to that found in the patient with periodic paralysis and myotonia. Draggen mice have myotonia and suffer from intermittent hind-limb immobility attacks. In-depth characterization of draggen mice uncovered novel systemic metabolic abnormalities in Scn4a mouse models and provided novel insights into disease mechanisms. We discovered metabolic alterations leading to lean mice, as well as abnormal AMP-activated protein kinase activation, which were associated with the immobility attacks and may provide a novel potential therapeutic target.

Keywords: SCN4A; mice; AMPK; periodic paralysis; myotonia

Abbreviation: AMPK = AMP-activated protein kinase
Introduction

The voltage-dependent sodium skeletal muscle α-subunit Na_1.4 channel, encoded by the SCN4A gene, is responsible for the initiation and propagation of the action potential in the muscle fibres that results in muscle contraction. Other ion channels in muscle fibre membranes (potassium, calcium and chloride channels) control the resting membrane potential, the repolarization following an action potential, and the Ca^{2+} entry into the cytoplasm that governs the contraction and the relaxation of the muscles. There are many pathological mutations found in the SCN4A gene leading to changes in the electrophysiological properties of the Na_1.4 channel and in muscle fibre excitability (Cannon, 1996a, 2006; Webb and Cannon, 2008).

The Na_1.4 channel is a large protein composed of four homologous domains (I–IV), each with six transmembrane helices (S1–S6). The majority of causative SCN4A mutations are missense, gain of function mutations (Tsuji et al., 2003; Jurkat-Rott et al., 2010; Lossin et al., 2012), and are usually located within the pore forming segments S5–S6, the voltage sensor segment S4 or the S4–S5 linker of the Na_1.4 channel. There are a number of clinically classified types of muscle channelopathies caused by mutations in the SCN4A gene (Vicart et al., 2005), including: potassium-aggravated myotonia, paramyotonia congenita, hyperkalaemic periodic paralysis and hypokalaemic periodic paralysis. The defining features of SCN4A skeletal muscle channelopathies are myotonia and/or muscle weakness (Fontaine et al., 1990; Cannon, 1996b). Periodic paralysis is characterized by reduced muscle membrane excitability, resulting in attacks of muscle weakness (Fontaine et al., 1990; Rojas et al., 1991; McClatchey et al., 1992). The attacks are often associated with increased (hyperkalaemic periodic paralysis) or reduced (hypokalaemic periodic paralysis) serum potassium levels. Myotonia is in turn characterized by increased muscle membrane excitability, leading to muscle stiffness (Matthews et al., 2010). There is some overlap in the clinical symptoms; for example patients diagnosed with hyperkalaemic periodic paralysis and paramyotonia congenita can present with attacks of both myotonia and paralysis. In a recent attempt to categorize patients with hyperkalaemic periodic paralysis, three clinical subgroups were proposed depending if patients presented without myotonia, with clinical or EMG myotonia or with paramyotonia congenita (Charles et al., 2013). In addition, the same SCN4A mutation can be found in patients with different clinical diagnosis (Sasaki et al., 1999; Okuda et al., 2001; Jurkat-Rott and Lehmann-Horn, 2007). Overall, there is little known about the consequences of SCN4A mutations in the muscles downstream of their impact on the electrophysiology of the Na_1.4 channel.

In recent years two knock-in mouse models of periodic paralysis have been generated to study the effects of Scn4a mutations on skeletal muscle function. The first Scn4a knock-in model carries the mouse equivalent of the most common human hyperkalaemic periodic paralysis mutation (M1592V) (Hayward et al., 2008). Heterozygous mice develop myotonia and progressive myopathy, together with ex vivo potassium-aggravated muscle weakness. The other knock-in strain models hypokalaemic periodic paralysis via another Scn4a mutation (R669H) (Wu et al., 2011). More recently a Cacna1s knock-in model of periodic paralysis has been developed (Wu et al., 2012).

Skeletal muscle is a major metabolic regulator where ATP homeostasis is critical for its function. Conversely, pathological alterations in skeletal muscle can lead to a disruption in the whole body metabolic balance (Pedersen and Febbraio, 2012). Muscles convert the chemical energy of carbohydrates and fats first into chemical energy (ATP) and then into mechanical work and heat. The use of energy in the form of ATP during muscle contraction leads to an increase in the concentrations of AMP and ADP that in turn activate AMP-activated protein kinase (AMPK) via phosphorylation at its Thr172 residue (Hardie and Sakamoto, 2006). As a consequence, active AMPK inhibits anabolic and activates catabolic pathways to increase the rate and capacity of ATP production (Winder and Hardie, 1996; O’Neill et al., 2013). AMPK signalling is therefore regarded as a key regulator of energy status in muscle fibres. Ion channels control muscle contractile activity and thus can affect ATP turnover in muscle fibres. AMPK activation has been reported to regulate ion channel activity directly (Evans et al., 2012) and indirectly (Light et al., 2003), thus providing a link between cellular energy demands and ion channel activity (Ingwersen et al., 2011; Andersen and Rasmussen, 2012).

Here we report the identification of a novel dominant SCN4A mutation identified in a patient presenting with myotonia and periodic paralysis. We also report the identification of the mouse equivalent of this mutation, which we named draggen, found in an N-ethyl-N-nitrosurea (ENU) mutagenesis screen (Nolan et al., 2002; Acevedo-Arozena et al., 2008). In-depth characterization of draggen mice, a novel mouse model of myotonia and periodic paralysis, found alterations in whole animal metabolism caused by Scn4a mutations accompanied by inappropriate AMPK activation in mice.

Materials and methods

Ethics statement

Consent for all neurophysiological tests was obtained, with tests performed as previously described (Fournier et al., 2004, 2006; Tan et al., 2011). All animal studies were carried out in accordance with UK Home Office legislation and local ethical guidelines. Mouse characterization followed ARRIVE guidelines.

Mice

Mice were kept under a controlled 12-h light cycle and had free access to water and were fed ad libitum on a commercial diet (SDS). Draggen mice were identified in the course of a dominant modifier ENU screen (Acevedo-Arozena et al., 2008). Briefly, BALB/c male mice were intraperitoneally injected twice with 100 mg/kg ENU at 12 weeks of age and crossed to congenic C57BL/6J females. An individual draggen G1 founder showing intermittent hind-limb immobility or dragging attacks was initially identified and subsequently backcrossed onto C57BL/6J to assess inheritance. Affected individuals from the initial backcross showing hind-limb dragging attacks were used for a genome-wide scan that identified a critical region on mouse
A novel SCN4A mutation and mouse model

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A novel mutation in SCN4A leads to myotonia and periodic paralysis

Young and adult male wild-type and draggen littermate (n = 5 per genotype). Young wild-type and non-affected males at 8–9 weeks of age (n = 4 per genotype), and 60-week-old wild-type and non-hind-limb dragging females (n = 4 per genotype) were also evaluated.

For chronic EMG, three draggen male mice were implanted with a wireless EMG system (Data Sciences F20-EET, Gold system). A transmitter was surgically implanted through an incision on the back, with leads from the transmitter leading, subcutaneously, to the right hind limb. Two electrodes for the EMGs were attached to the gastrocnemius muscle. The surgeries were conducted with the mouse under ketamine–xylazine anaesthesia. A post-surgery period of 1 week was given to each mouse to ensure a full recovery. At the end of the recovery period, we recorded the EMG signal uninterruptedly. Sampling rate was 500 Hz and data were processed using SleepSign software (Kissei Comtec). The mice were singly housed and free to move in the cage. We continuously acquired videos with a computer synchronized with the EMG recordings. Videos were visually scored and immobility attacks were identified by at least two independent observers.

Physiological assessment of muscle force and in vitro electrophysiology analysis

For physiological assessment of muscle force and in vitro electrophysiology analysis, see the online Supplementary material.

Histology

Young and adult male wild-type and draggen littermate (n = 3) hind-limb muscles (tibialis anterior, extensor digitorum longus, gastrocnemius and soleus) were dissected at staged ages, weighed and snap frozen and 10-μm sections were cut in a cryostat. Tibialis anterior sections were stained using haematoxylin and eosin (and NADH-tetrazolium reductase) and an antibody-based stain for myosin heavy chain isoforms (Ila and IIb) as previously published (Bloemberg and Quadrilatero, 2012), with Alexa Fluor® 488 and 555 as secondary antibodies. Fibre numbers were recorded using ImageJ software (NIH). Fibre cross-sectional areas were measured for different fibre types (tibialis anterior, soleus) and fibre count and type percentages were assessed. For pups: post-natal Day 0 pups were sacrificed and formalin fixed. They were cut in longitudinal body halves and sections were stained with haematoxylin and eosin.

Transmission electron microscopy

Mice were perfused with a mix of 2% glutaraldehyde and 2% paraformaldehyde in PBS. Hind-limb muscles were dissected and placed in 1% OsO4 on ice for 1 h followed by two 5-min washes with phosphate buffer (100 mM Na2HPO4/NaH2PO4, 2H2O). The samples were dehydrated through an ethanol series (30%, 50%, 70%, 95% and absolute) and transferred to a 1:1 mixture of Epon/Araldite and acetone and incubated overnight with mixing. The solution was then replaced with a 1:1 mixture of 100% Epon/Araldite and incubated for 6 h, followed by another replacement with fresh Epon/Araldite and overnight incubation with mixing. Samples were transferred to fresh Epon/Araldite in embedding moulds and orientated as required. Polymerization of the Epon/Araldite mould was completed at 65°C for 48 h. Seventy nanometre sections were produced and stained with saturated uranyl acetate and Reynolds' lead citrate. All images were obtained with a Tecnai 12 BioTWIN made by FEI.

Immuno-blot analysis

Primary antibodies against p-AMPKα (Thr172) and total AMPKα were obtained from Cell Signalling. Tibialis anterior and extensor digitorum longus muscles from draggen, M1592V and age-matched wild-type littersmate controls were homogenized in 10 volumes of RIPA buffer (with phosphatase and protease inhibitor cocktails from Roche). After spinning the homogenate at 12000 g at 4°C, the supernatant was used for western blot analysis using pre-cast SDS gels (Invitrogen). The Odyssey infrared imaging system (Li-Cor) was used for band detection and quantification.

Statistical analysis

Data is presented as the mean ± standard error of the mean (SEM). Comparisons between two groups were made using the two-tailed Student’s t-test and Mann-Whitney. ANOVA with post hoc analysis (Bonferroni and Tukey) was used as appropriate. For survival and age-at-onset analysis, the Log-Rank test was performed. P-values were determined by SPSS v.19 software. P ≤ 0.05 was considered statistically significant.

Results

A novel mutation in SCN4A leads to myotonia and periodic paralysis

A novel SCN4A mutation was identified in a patient presenting with myotonia and periodic paralysis. The mutation identified (c.1762A > G;p.I588V, SCN4A[588V]) is located within the transmembrane S1 region of domain II. Mutations within this region have not been previously identified as causative of myotonia or
periodic paralysis. The I588V mutation has not been documented in the exome variant server, 1000 Genomes, Leiden Open Variation Database or dbSNP. The 70-year-old male patient presented with a history of muscle stiffness and weakness from the age of eight. The stiffness was worst in his calves and worsened by exertion. The patient also noted episodes of weakness that were precipitated by running which would persist for weeks before complete resolution. In the past few years the episodes of weakness became more frequent, severe and prolonged, occurring once every 2–3 weeks. The episodes of stiffness have also persisted, primarily occurring following rest after exertion, with no reported sensitivity to cold. There is evidence of a family history (Fig. 1A), with a severely affected younger brother, father and paternal grandmother. The patient’s three daughters and two sisters are reported to be unaffected but were unavailable for assessment. Physical examination of the patient demonstrated myotonia of the eyelids that did not worsen with exertion. The patient had normal tone and power and reflexes throughout but some atrophy of the calves was noted. Neurophysiological testing demonstrated the presence of myotonia that worsened after the muscles were cooled (data not shown). Short exercise testing was normal both at room temperature and following cooling. In the long exercise test there was a decrease in amplitude of 38% and a concordant 58% of the area of the compound muscle action potential from baseline, which is abnormal (Tan et al., 2011) (Supplementary Fig. 1A). The history of episodic weakness and stiffness from childhood alongside evidence of myotonia and a positive long exercise test was consistent with a clinical diagnosis of hyperkalaemic periodic paralysis together with paramyotonia congenita.

**Generation of a novel mouse model (draggen) carrying the equivalent point mutation in Scn4a**

Through an unbiased large-scale ENU mutagenesis screen for dominant mutations (Nolan et al., 2000), we identified a mutant mouse, named draggen (Dgn/+) with unprovoked intermittent attacks of hind-limb dragging or immobility. After positional cloning, a missense mutation in the mouse *Scn4a* gene was identified in the critical region of mouse chromosome 11, which segregated with the intermittent dragging phenotype. Once the mutation was identified, the colony was subsequently maintained by genotyping, in the critical region of mouse chromosome 11, which segregated

To evaluate the electrophysiology of the novel Scn4aI582V and SCN4A[I588V] mutations, HEK293 cells were transfected with cDNA coding for the mouse or human wild-type or mutant Na\(_{\text{v}}\).1.4 channel. Channel properties were analyzed using whole-cell patch clamp. Voltage dependence of channel activation was shifted 6 mV in the hyperpolarizing direction in the mutant for both mouse and human clones (P < 0.005, n = 10–25) (Fig. 1C, Supplementary Fig. 1C and Table 1), suggesting a gain of function. The voltage dependence of fast inactivation was shifted 3 mV in the hyperpolarizing direction for both mouse and human mutant channels [P = 0.06 for mouse clone (n = 13–15), P < 0.01 for human clone (n = 18–20)] (Fig. 1C, Supplementary Fig. 1C and Table 1). No significant differences were detected in the voltage dependence of slow inactivation (Fig. 1C, Supplementary Fig. 1C and Table 1).

**Myotonia and hind-limb immobility attacks in draggen mice**

Draggen mice (*Scn4a*<sup>Dgn</sup>+/−) suffered from unprovoked intermittent hind-limb immobility attacks when the mouse was not able to move the hind-limbs. This was followed by a total recovery in mobility after a short period of time usually lasting a few seconds (Supplementary Video 1). To systematically assess the hind-limb dragging onset and frequency, mutant mice were subjected to a test once a week from 3 weeks of age; hind-limb immobility attacks were scored as present or absent. Through this process, a clear difference in the penetrance of the observed intermittent dragging phenotype was noted between male and female mutant mice (Fig. 2A, P < 0.001). All males carrying the draggen mutation showed at least one hind-limb immobility episode by 60 weeks of age (100% penetrance), with an average age at onset of ~16 weeks of age. However, only 38% of draggen females displayed an episode at least once during the same period, with an average age at onset of ~25 weeks of age, which is significantly different from that observed in males (P = 0.013). For those mice showing the intermittent attacks, there is a large variation in the age at which the first attack is detected, with extreme cases showing the first episode as early as weaning (3 weeks of age) or as late as 50–60 weeks of age. In addition, the frequency of hind-limb dragging attacks that was observed over the lifetime of individual mice was also different between males (average 8 ± 0.9 episodes up to 60-weeks of age) and affected females (2.6 ± 0.4 episodes; P < 0.001).

As the proband presented with myotonia, draggen mice were subjected to electromyography (EMG) of hind-limb muscles. Mutant mice showed striking myotonic runs after light movement of the needle that were not present in wild-type littermate controls (Fig. 2B). Interestingly, myotonia was present in all of the draggen mice assessed. These included young males tested before their first recorded dragging attack, as well as aged draggen females that never had any recorded hind-limb immobility event (data not shown). Hence, myotonia is fully penetrant in draggen mutants, including females that have never shown a dragging episode based on our scoring system.

To study the muscle activity during the hind-limb immobility attacks, we performed chronic, wireless EMG on freely moving singly housed draggen males. We synchronized the EMG
recordings with video monitoring to focus on the EMG activity during the dragging events. The intermittent immobility attacks were accompanied by high EMG activity, which continued throughout the whole event (Fig. 2C and Supplementary Fig. 2). Overall, this intense EMG activity suggests that the immobility or dragging attacks are not produced by muscle weakness in draggen mice.

The draggen mutation is homozygous lethal

Heterozygous draggen mice (Scn4a\textsuperscript{Dgn/+}) had a normal lifespan up to 2 years of age (Supplementary Fig. 3A). However, although homozygous draggen mice (Scn4a\textsuperscript{Dgn/Dgn}) are born at Mendelian

Table 1  Electrophysiological properties of wild-type and mutant Na\textsubscript{v}1.4 channels

<table>
<thead>
<tr>
<th>Clone</th>
<th>Activation</th>
<th>Fast inactivation</th>
<th>Slow inactivation</th>
</tr>
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<tr>
<td></td>
<td>n</td>
<td>V1/2 (mV)</td>
<td>n</td>
</tr>
<tr>
<td>hWT</td>
<td>25</td>
<td>$-18.8 \pm 0.7$</td>
<td>20</td>
</tr>
<tr>
<td>I588V</td>
<td>21</td>
<td>$-24.8 \pm 0.6^{***}$</td>
<td>18</td>
</tr>
<tr>
<td>mWT</td>
<td>12</td>
<td>$-17.5 \pm 0.6$</td>
<td>15</td>
</tr>
<tr>
<td>Draggen</td>
<td>10</td>
<td>$-23.1 \pm 1.1^{***}$</td>
<td>13</td>
</tr>
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Voltage values at which half of the channels (V1/2) were activated (Activation) or inactivated (fast and slow inactivation) and the offset current (C) of slow inactivation are stated for human and mouse wild-type (hWT and mWT), human I588V and Draggen mouse (I582V) mutant channels. Statistical comparisons are between the wild-type and mutant clones. **P < 0.01, ***P < 0.001.

A novel SCN4A mutation and mouse model
ratios from heterozygous intercross matings (21 Scn4aDgn+/Dgn from a total of 90 pups born), we did not observe any homozygous pups older than 2 days. Scn4aDgn+/Dgn mice died perinatally with noted breathing difficulties, confirmed by the observation of collapsed lungs (Supplementary Fig. 3B), but otherwise morphologically normal organs. Notably, skeletal muscle, including diaphragm, was also morphologically normal (data not shown), suggesting that the cause of death may be due to a functional impairment of muscles required for breathing and suckling.

To confirm that the homozygous lethality was due to the Scn4a draggen mutation, an allelic complementation cross was performed with a previously generated Scn4a knock-in mouse strain (Scn4aM1592V+/+ (Hayward et al., 2008). Scn4aDgn+/M1592V compound mutant mice were born at Mendelian ratios (15 Scn4aDgn+/M1592V out of 59 pups born) but also died perinatally with similar difficulties in breathing and lung morphology (Supplementary Fig. 3C). We therefore concluded that the lethality was due to Scn4a allelic non-complementation.

Reduced muscle force generated by draggen muscles

Muscle force, measured by grip-strength (Supplementary Fig. 4A), and motor coordination, measured as locotronic performance (Supplementary Fig. 4B), progressively deteriorated in draggen mice. To further assess muscle force in vivo, the physiology of the hind-limb tibialis anterior and extensor digitorum longus muscles were studied in a cohort of wild-type and draggen male littermates at 60 weeks of age. For both the tibialis anterior and extensor digitorum longus muscles, the time at which maximum contraction (Tmax) and half relaxation (T1/2R) were achieved was significantly higher in draggen mice compared to wild-type littermates (Fig. 3A and B, P < 0.001 for all comparisons). Moreover, the single twitch force (Fig. 3B) and the maximum force generated by the extensor digitorum longus muscles (Fig. 3C) were lower in draggen mice when compared with wild-type (P < 0.001 for all comparisons). This was not due to a difference in tibialis anterior and extensor digitorum longus muscles weight (data not shown). Fast-twitch muscles, such as the extensor digitorum longus, normally fatigue rapidly and cannot maintain force when repeatedly stimulated, whereas slow-twitch muscles are more resistant to fatigue. Typical fatigue traces show that the extensor digitorum longus of draggen mice becomes more fatigue-resistant after stimulation (Fig. 3D). The fatigue index of draggen extensor digitorum muscles was almost double that of the wild-type littermate controls (P < 0.001). This is usually observed in slow-twitch muscles and muscles adapted to repeated contractile activity or endurance training, suggesting potential metabolic changes.
Figure 3  Draggen mice have muscle weakness. In vivo physiological assessment of hind-limb muscles of 60-week-old male mice. 

Scn4a+/+ (n = 12); Scn4aDgn/+ (n = 14). (A) Tibialis anterior (TA) muscle force showed that the time to peak force (Tmax) and half-time relaxation time (T1/2R) were significantly longer in draggen mice than wild-type controls. For Tmax (Scn4a+/+ = 17.5 ms; Scn4aDgn/+ = 21.9 ms; P < 0.001). For T1/2R (Scn4a+/+ = 13.3 ms; Scn4aDgn/+ = 20.6 ms; P < 0.001). Single twitch force for tibialis anterior muscles was not significantly different between wild-type and draggen muscles (Scn4a+/+ = 54.1 g; Scn4aDgn/+ = 45.7 g; P = 0.19). The two traces shown per image represent the right and left hind-limb from the same animal. (B) Extensor digitorum longus (EDL) muscles in draggen mice also took longer to reach both Tmax and T1/2R than wild-type (Tmax: Scn4a+/+ = 15.9 ms; Scn4aDgn/+ = 20.0 ms; P < 0.001. T1/2R: Scn4a+/+ = 10.7 ms; Scn4aDgn/+ = 17.3 ms; P < 0.001). Single twitch force was also determined for extensor digitorum longus muscles, with wild-type muscles exerting more force than draggen muscles (Scn4a+/+ = 16.7 g; Scn4aDgn/+ = 9.8 g; P < 0.001). (C) Extensor digitorum longus tetanic force generated by draggen mice (45.8) is reduced compared to wild-type littermates (60.5) (P = 0.003). (D) Representative traces of tetanic tension from wild-type and draggen extensor digitorum longus muscles. The fatigue index (FI) is increased for draggen muscle (0.48) when compared to wild-type (0.25) (P < 0.001). (E) High potassium levels diminish force generated by extensor digitorum longus muscles of draggen mice ex vivo. Scn4a+/+ (n = 7); Scn4aDgn/+ (n = 9) (P-values: 14 min; P = 0.017; 16–20 min; P < 0.003). The force generated by extensor digitorum longus was measured every 2 min with muscles submerged in a bath with normal (4.75 mM) and high (12 mM) potassium concentrations for 10 min in each condition. Data are expressed as mean ± SEM. *P < 0.05; **P < 0.01; ***P < 0.001.
in draggen muscle. Motor units were also estimated in the extensor digitorum longus muscles of wild-type and draggen mice and no significant differences were observed (P = 0.6, data not shown), suggesting that the muscle weakness and fatigue characteristics in draggen mice are not caused by denervation or axon/motor unit dysfunction.

High extracellular potassium levels can elicit muscle weakness in draggen muscle

Periodic paralysis is characterized by attacks of muscle weakness, which can be elicited in some patients by changes in extracellular potassium levels (Moxley et al., 1989; Vicart et al., 2004; Hayward et al., 2008). The effect of different potassium levels in muscle force was therefore measured ex vivo in the extensor digitorum longus from 60-week-old wild-type and draggen male mice in the presence of low (2 mM), normal (4.75 mM) and high (12 mM) potassium levels. Wild-type extensor digitorum longus muscles exerted similar maximal force in all conditions. In contrast, (12 mM) potassium levels. Wild-type extensor digitorum longus muscles showed progressive muscle weakness pathology, mimicking the muscle pathology seen in some myotonia and patients with periodic paralysis (Bradley et al., 1990; Tengan et al., 1994; Feng et al., 2009, 2011; Luan et al., 2009).

Metabolic abnormalities in draggen mice

Male draggen mice, but not females, showed significantly reduced weight gain from 12 weeks of age compared to wild-type littermates (Fig. 6A and Supplementary Fig. 5A). The weight differences in males were not due to differences in body size, measured via femoral bone X-ray, or in food consumption, measured on a 24-h cycle (data not shown). Importantly, similar results were obtained when comparing the weights of wild-type and Scn4aM1592V/+ male mice (Supplementary Fig. 5B). To further dissect differences in body composition, the amount of fat and lean mass was measured using Echo-MRI at 18 weeks of age. Draggen male mice displayed less total fat mass than their wild-type littermates (Fig. 6B; P = 0.015). As draggen male mice have less fat mass yet consume similar amounts of food as wild-type littermates, their whole body energy expenditure was measured. Draggen mice had significantly higher whole body energy expenditure than wild-type littermates when we controlled for total body weight in the dark period of a 24h cycle (Fig. 6C, P = 0.01). Weight differences might also be explained by differences in circulating leptin levels (Oswal and Yeo, 2010). We found a trend towards a reduction in serum leptin levels in draggen mice compared to wild-type at 40 weeks of age (Supplementary Fig. 5C, P = 0.07). We also tested glucose metabolism and found that draggen mice re-established plasma glucose levels more efficiently than wild-type littermates following a glucose tolerance test (Fig. 6D), despite similar baseline insulin levels (Supplementary Fig. 5D). In summary, mutations in the muscle specific Scn4a gene have profound effects on the general metabolic status of the whole animal.

AMPK is constitutively activated in draggen and Scn4aM1592V/+ skeletal muscle in mice with hind-limb immobility

As muscle is a major contributor to the whole body energy expenditure and metabolic rate, we speculated that the systemic
metabolic alterations in draggen mice may be a consequence of disturbed muscle energy demand that is required to re-establish ion balance in myotonic muscle or after intermittent immobility attacks. Muscle contractions increase the rate of ATP hydrolysis which, via increases in the concentrations of AMP and ADP, activates the key intracellular energy sensor AMPK (Winder and Hardie, 1996; Friedrichsen et al., 2013), mainly via phosphorylation of Thr172 (Hawley et al., 1996; Mu et al., 2001). We therefore hypothesized that the metabolic alterations seen in draggen male mice may be mediated by differential AMPK activation in mutant muscles. To estimate AMPK activation, Thr172 phosphorylation was measured from tibialis anterior muscle in wild-type and draggen male mice at two ages: young (12 weeks) and aged (60 weeks). Total AMPK levels were similar between all genotypes at both ages. However, when compared to wild-type littermates, AMPK Thr172 phosphorylation was higher in both young and aged tibialis anterior muscles of draggen mice that have shown at least one immobility episode (Fig. 7A). Moreover, AMPK activation levels were also higher in the tibialis anterior of the $\text{Scn4a}^{M1592V/+}$ mice (Fig. 7B), which also showed intermittent

Figure 4 Progressive myopathy in draggen mice. (A) Pathological assessment of tibialis anterior (TA) muscle of 60-week-old male wild-type and draggen littermates. Haematoxylin and eosin (H&E) of the tibialis anterior cortex shows central nuclei and hypertrophic muscle fibres in draggen muscle (delimited in yellow area to show the size of one draggen fibre for comparison). Yellow arrows point to central nuclei. (B) Quantification of the central nuclei in the muscle fibres of wild-type and draggen tibialis anterior muscles ($n=3$ mice per group, $n=3$ fields per mouse; $P=0.05$). (C) NADH-TR activity staining shows more oxidative fibre grouping in the core of the draggen tibialis anterior muscles. (D) Higher magnification of the core of the tibialis anterior muscle stained with NADH-TH showing enlarged high oxidative fibre grouping in the draggen mice compare to the wild-type. (E) Quantification of fibre size (CSA, cross section area) in the tibialis anterior core and cortex showing enlarged high and low oxidative draggen fibres when compared to wild-type ($n=3$ per group, $P<0.001$ for both comparisons). (F) Representative MHC staining showing the fibre type in the tibialis anterior muscle of 12-week-old mice wild-type and draggen littermates (Ila fibres in green and Iib fibres in red). (G) Quantification of the total number and the percentage of Ila and Iib fibres. ($\text{Scn4a}^{+/+}$ $n=8$; $\text{Scn4a}^{Dgn/+}$ $n=6$ mice, $P=0.002$ for both comparisons). Data are expressed as mean $\pm$ SEM. *$P<0.05$; **$P<0.01$. Scale bars: A = 50 $\mu$m; C and F = 500 $\mu$m; D = 100 $\mu$m.
Figure 5 Tubular aggregates and vacuoles in skeletal muscle of draggen mice. Transmission electron microscopy analysis of the tibialis anterior muscle from draggen (A–D) and control mice (E and F). (A) Representative view of single-walled tubular aggregates that have accumulated between myofibrils. (B) Longitudinal section showing triads of different morphological appearances (filled arrows). Note the presence of densities between adjacent membranes (open arrows). (C) Detailed view of T tubules and sarcoplasmic reticulum of triads (filled arrows) of irregular size and orientation. (D) Detailed view of a tubular aggregate region showing the continuity of the sarcoplasmic reticulum from a presumed irregular triad (filled arrow) with a large vesicle (star). (E and F) Wide and detailed view, respectively, of triads of normal size and orientation (arrows) from a control sample.
immobility attacks using our scoring system. Surprisingly, this steady-state activation of AMPK is not observed in draggen mice that have not shown a hind-limb immobility episode using our scoring system (Fig. 7C), despite all tested draggen mice having underlying myotonia. Thus, higher activation levels of AMPK may be a general feature of mouse models carrying Scn4a mutations presenting with intermittent immobility attacks.

The higher basal levels of activated AMPK in draggen muscle suggest a possible functional link between AMPK activation levels and Na\textsubscript{1.4} channel physiology. We therefore investigated if AMPK activation could directly modify the electrophysiology of Na\textsubscript{1.4} channels \textit{in vitro}. HEK293 cells transfected with Na\textsubscript{1.4} variants were incubated with the AMPK activator AICAR or cotransfected with a constitutively active truncated AMPK clone AMPK\textsubscript{Ca1}(1–312). In these conditions, changes in AMPK activation levels did not have any effects on voltage dependence of wildtype or mutant Na\textsubscript{1.4} channel activation or fast inactivation (Supplementary Fig. 6). Thus, at least \textit{in vitro}, AMPK activation is not sufficient to significantly alter the electrophysiology of the Na\textsubscript{1.4} channel.

**Blunted AMPK activation in draggen muscles after \textit{in vivo} stimulation**

In patients, attacks of periodic paralysis can occur after physical exertion, implying a potential link between energy demand and paralysis episodes. To mimic exercise in the mice, we tetanically stimulated the tibialis anterior and extensor digitorum longus muscles of mice that have been previously used for the above \textit{in vivo} physiology recordings and measured AMPK activation levels. Remarkably, muscles from draggen mice that had previously shown immobility episodes were not able to activate AMPK to the same degree as wild-type littermate controls after the tetanic stimulation (Fig. 7D). Thus, AMPK activation is perturbed, both in basal conditions and after stimulation in draggen muscles.
Discussion

Here we report a novel pathological mutation in the SCN4A gene in a patient presenting with myotonia and periodic paralysis. We have also produced its mouse model, draggen, carrying the equivalent point mutation in the mouse Scn4a gene. All tested draggen mice had myotonia, and all draggen males and a subset of draggen females also developed spontaneous hind-limb immobility attacks. This is underlined by a progressive myopathy and muscle fibre switching towards a more oxidative type.

Figure 7 Changes in AMPK activation levels in mutant Scn4a hind-limb muscle. Immuno-blot analysis of mouse tibialis anterior muscle lysates using antibodies to activated AMPK (Phospho-AMPKα (Thr172)) and total AMPK levels (α1-α2). AMPK activation is expressed as the coefficient between the p-AMPK/total-AMPK band intensities; graph values are relative to the average of each wild-type group. Protein loading was controlled by GAPDH (data not shown). (A) Representative images of immunoblots from young (12-week-old) and aged (60-week-old) wild-type or draggen mutant mice. In draggen mice the level of activated AMPK is higher than wild-type (n = 6 per genotype; P = 0.02). (B) Representative images of immunoblots from tibialis anterior muscle of wild-type and Scn4aM1592V+/+ mice, showing higher basal AMPK activation in Scn4aM1592V+/+ (n = 4) when compared to wild-type (n = 3); P = 0.04. (C) Representative images of immunoblots from wild-type and draggen littermates that have not shown a hind-limb dragging attack (NA) and draggen mice that have already shown immobility attacks (A). AMPK activation is elevated only in draggen mice that have already shown immobility attacks (n = 4 per group; wild-type versus NA, P = 0.4; wild-type versus A, P = 0.03; A versus NA, P = 0.04). (D) Representative immunoblots of tetanically stimulated tibialis anterior and extensor digitorum longus muscles lysates from 60-week-old wild-type and draggen littermates mice induced after in vivo physiology recordings (including muscle force, fatigue characteristics and estimation of motor units). The quantification graph shows blunted AMPK activation levels in draggen muscles after stimulation when compared to wild-type (n = 6 in both groups; P < 0.001). Data are expressed as mean ± SEM. *P < 0.05; ***P < 0.001.
Interestingly, male draggen mice have systemic metabolic abnormalities, including diminished fat mass and improved glucose tolerance. This is accompanied by changes in AMPK activation, both in basal conditions and after muscle stimulation, in mice that present with dragging attacks.

The majority of dominant SCN4A causative mutations in periodic paralysis with myotonia have been found in the pore forming segments S5–S6 or the voltage sensor segment S4 of Na⁺v1.4. The mutation identified here is located in the transmembrane segment S1 of domain II, where no other SCN4A mutations have been previously described. There are other mutations in the homologous S1 segment of domain IV of the Na⁺v1.4 channel (Wagner et al., 1997) presenting features of hyperkalaemic periodic paralysis and paramyotonia congenita with reported gender differences. There are also reported mutations in the homologous S1 residue of domain I of the Na⁺v1.4 channel (Petitprez et al., 2008), as well as in another sodium voltage-gated paralogue (Na⁺v1.7) (Cheng et al., 2008) that cause similar effects to I588V, causing a hyperpolarizing shift in the voltage dependence of activation. The hyperpolarizing shift in the voltage dependence of activation found in I588V Na⁺v1.4 channels is found for several mutations associated with myotonia (Petitprez et al., 2008; Kokunai et al., 2012; Yoshinaga et al., 2012), and would lower the activation channel threshold and contribute towards myotonia. Depolarization caused by increased sodium channel activity and the small enhancement of fast inactivation may contribute towards reduced Na⁺v1.4 channel availability and muscle weakness. Many hyperkalaemic periodic paralysis mutations display attenuated slow inactivation whereas the slow inactivation of I588V mutant channel was wild-type like. However, some hyperkalaemic periodic paralysis mutations present with intact or increased slow inactivation (Hayward et al., 1999; Bendahhou et al., 2000), suggesting that Na⁺v1.4 mutations can lead to hyperkalaemic periodic paralysis without disruption of slow inactivation.

We were able to elicit muscle weakness ex vivo in draggen muscles by increasing the extracellular potassium concentration. However, although highly statistically significant, the drop in muscle force (~25%) in draggen muscle after increasing [K⁺] was less pronounced than the drop previously published in Scn4a<sup>M1592V/+</sup> muscles; a drop in muscle force of ~70% that was confirmed with our experimental set-up (data not shown). This may correlate with the fact that in vitro these novel human and draggen mutations had only small effects on voltage dependence channel inactivation. Indeed, the intermittent attacks seen in draggen mice are accompanied by high EMG activity, suggesting that they are not produced by muscle weakness. Nevertheless, in the patient described here, the I588V SCN4A mutation unequivocally leads to myotonia and periodic paralysis.

Importantly, we report a progressive myopathy in draggen mice, with the appearance of tubular aggregates, vacuoles and associated muscle atrophy. Thus, it is not surprising to find reduced muscle force in aged draggen mice. Although we did not see any tubular aggregates in our control muscles, it should be noted that tubular aggregates have been previously reported in aged inbred mice and could be a consequence of the ageing process (Agbulut et al., 2000). However, similar pathological features have been described in cases of periodic paralysis and myotonia (Bradley et al., 1990; Schoser et al., 2007; Luan et al., 2009; Feng et al., 2011). Therefore, draggen mice offer a novel excellent model to study the role of tubular aggregates and vacuoles in the pathophysiology of SCN4A channelopathies.

During the course of this investigation, we analysed Scn4a<sup>M1592V/+</sup> mice that have previously been characterized but were not reported to develop intermittent hind-limb dragging attacks (Hayward et al., 2008). Using our scoring system, we were able to detect hind-limb immobility attacks on Scn4a<sup>M1592V/+</sup> mice that were indistinguishable from those seen in draggen mice (data not shown). The previous absence of reported immobility attacks in Scn4a<sup>M1592V/+</sup> may be due to differences in the genetic background between the strain used here and that used in the initial characterization of the Scn4a<sup>M1592V/+</sup> mice (Hayward et al., 2008).

The draggen mutation causes EMG myotonia in all tested draggen males and females, indicating full penetrance of this phenotype. However, this is not the case for the intermittent immobility events; the mutation affects all males, but only a subset of mutant females. These sex differences are not explained by differences in Scn4a allelic expression levels between males and females (data not shown). This suggests that modifying factors differing between males and females, other than the mutation itself, may have an impact on the biophysics of the mutant Na⁺v1.4 channel, making males more prone to suffer from immobility attacks. Sex differences in phenotypic penetrance have been previously reported in forms of periodic paralysis (Wagner et al., 1997; Kim et al., 2004; Li et al., 2012; Ke et al., 2013) and in a mouse model of hypokalaemic periodic paralysis (Wu et al., 2011). The identification of these potential sex-specific modulating factors could make them attractive targets for therapeutic intervention.

To investigate possible factors that might modify the properties of the mutant Na⁺v1.4 channel, we looked into the whole body metabolism of draggen mice. Lower body weight in draggen males was accompanied by general metabolic alterations, including enhanced whole body energy expenditure and glucose tolerance, which together potentially contribute to the leaner phenotype. Importantly, we also observed weight differences between Scn4a<sup>M1592V/+</sup> and wild-type males. Overall, these data show that mutations in the muscle specific Scn4a gene can produce systemic metabolic alterations.

We hypothesized that the leaner phenotype seen in draggen males could reflect differences in energy homeostasis. Indeed, basal AMPK activation levels are higher in draggen muscles that have shown at least one episode of hind-limb dragging. This could potentially explain the glucose tolerance (Friedrichsen et al., 2013) as well as the higher energy expenditure phenotypes in draggen males. However, AMPK activation was not significantly increased in draggen muscle before showing at least an immobility episode reported using our scoring system. This suggests that myotonia alone may not be sufficient to drive the increase in steady-state AMPK activation levels. However, the severity of myotonia may vary between individual draggen mice; in this scenario, mice with the more severe myotonia could have more involuntary contractile activity, presented as episodes of immobility, leading to a depletion of energy and a subsequent activation of AMPK. This, in turn, could result in endurance training-like adaptations such as blunted
AMPK activation after stimulation (Mortensen et al., 2013). Interestingly, baseline AMPK activation levels were also higher in Scn4a+/-/mice muscles, confirming that the rise in AMPK activation levels is not unique to draggen muscles and could be a generalized feature of Scn4a mouse models showing myotonia and hind-limb dragging attacks.

AMPK activation has been shown to affect the properties of ion channels expressed in skeletal muscle such as Kir2.1 and KATP channels (Alesutan et al., 2011; Yoshida et al., 2012), and might couple changes in metabolism to cell excitability. However, AMPK activation did not directly altered NaV1.4 channel behaviour in vitro. A thorough investigation of the electrophysiological properties of the muscle fibres would be required to further characterize the possible effects of AMPK activation on muscle excitability.

In conclusion, we have identified a novel SCN4A mutation in a human patient and created a mouse model carrying the equivalent point mutation. Both mutations implicate a novel NaV1.4 domain in the pathophysiology of myotonia and periodic paralysis. In depth characterization validated the draggen mice as an excellent new model to study the underlying muscle pathophysiology of the human conditions, and uncovered novel systemic metabolic abnormalities. These metabolic alterations are accompanied by changes in muscle AMPK activation levels, suggesting a potential role of the energy sensor AMPK in models of SCN4A channelopathies.

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Supplementary material

Supplementary material is available at Brain online.

References


A novel SCN4A mutation and mouse model


