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Migraine and Two-Pore-Domain Potassium Channels

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1 **Migraine**
2 **and**
3 **Two-Pore-Domain Potassium Channels**

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1 **Abstract**

2

3 Migraine is a common, disabling neurological disorder with a genetic, environmental
4 and hormonal component with an annual prevalence estimated at ~15%. It is characterized by
5 attacks of severe, usually unilateral and throbbing headache, and can be accompanied by
6 nausea, vomiting and photophobia. Migraine is clinically divided into two main subtypes:
7 migraine with aura, when it is preceded by transient neurological disturbances due to cortical
8 spreading depression (CSD), and migraine without aura. Activation and sensitization of
9 trigeminal sensory neurons, leading to the release of pro-inflammatory peptides, is likely a
10 key component in headache pain initiation and transmission in migraine. In the present
11 review, we will focus on the function of Two-Pore-Domain potassium (K_{2P}) channels which
12 control trigeminal sensory neuron excitability and their potential interest for developing new
13 drugs to treat migraine.

14

15 Key words: Migraine, trigeminal sensory neurons, K_{2P} channels, KCNK, heterodimerization,
16 frameshift mutation-induced alternative translation initiation (fsATI), allodynia, Kozac
17 sequence, excitability.

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1 Introduction

2 Migraine is one of the most common diseases world-wide, affecting nearly 15% of the
3 global population, with a women to men ratio of 3:1. Its societal and economic burden is
4 considerable (Burch and others 2015). Migraine manifests as a unilateral throbbing headache
5 and is accompanied by multiple symptoms such as nausea, vomiting, photophobia,
6 phonophobia or cutaneous allodynia. The migraine attack is often split into four different
7 phases following a temporal pattern that can last for several days: premonitory, aura,
8 headache and postdrome phase (Goadsby and others 2017) (Fig. 1). The premonitory phase
9 can begin as early as three days before the headache and is characterized by fatigue, mood
10 changes, food craving and yawning (Goadsby and others 2017). Around less than one third of
11 patients will develop an aura before the headache, which consists of visual and sensory
12 disturbances that will last from several minutes to a few hours. The underlying event is
13 thought to be a cortical spreading depression (CSD), a wave of brief depolarization followed
14 by a long-lasting depression of neuronal activity that propagates slowly in the brain (Charles
15 and Baca 2013). Then, the headache phase will start, lasting between 4 to 72 hours. The
16 migraine attack resolves with a postdrome phase, lasting from hours to days, and consisting of
17 residual headache, fatigue and impaired cognitive functions (Bose and others 2018). In
18 addition to the presence or not of aura, the frequency of headaches is used to further
19 differentiate episodic migraine (headache with or without aura that occurs 1 to 14 days per
20 month, for at least three months) or chronic migraine patients (at least 15 days of headache
21 per month for at least three months) (Adams and others 2015). A broad array of symptoms
22 contributes to the disability associated with migraine attacks and indicates involvement of
23 brain regions in homeostatic, autonomic, emotional and sensory processing, thus highlighting
24 a wide involvement of the nervous system in migraine (Vila-Pueyo 2018; Goadsby and others
25 2017). Imaging studies have confirmed that these non-pain symptoms and changes in the
26 brain are not simply responses to pain but can exist in the absence of headache and produce
27 functional imaging changes on their own (Denuelle and others 2007; Schulte and May 2016).
28 Therefore, migraine can be considered as a broad sensory disorder. Migraine patients display
29 abnormal responses toward pain (Nahman-Averbuch and others 2019) or light (Bernstein and
30 others 2019). Other differences lie on responses that should be adaptive but become impaired
31 or maladaptive, such as altered brainstem processing (Vila-Pueyo and others 2019), changes
32 in gray matter volume (Coppola and others 2017), impaired adaptive cerebral hemodynamic
33 mechanisms (Frederiksen and others 2019), habituation deficiency (Coppola and others 2005)
34 or metabolic impairment (Gross and others 2019). Due to the nature of the triggers reported

1 by patients (stress, sleep disorder *etc.*) (Karsan and Goadsby 2018; Turner and Houle 2018)
2 and a clear involvement of the hypothalamus) in the early phases of the attack, migraine is
3 considered as a deregulated response toward various stressful stimuli, highlighting the
4 difficulty of the brain to keep a physiological and stable state. Thus, migraine has been
5 described as a pathophysiology of allostasis (*i.e.* the responses that help to maintain
6 physiological stability) (Borsook and others 2012). Despite the broad impact of migraine, the
7 understanding of several aspects of its pathophysiology and underlying mechanisms remain
8 unclear.

9

10 [Initiation of migraine attacks: triggering factors and genetic aspects](#)

11 ***Triggering factors***

12 Among various external factors able to trigger migraine attacks, stress is the most
13 reported (Turner and Houle 2018). In clinical and preclinical context, methods for inducing a
14 migraine attack include the injection of triggering molecules, like the calcitonin gene-related
15 peptide (CGRP), for which elevated levels have been measured in patients during migraine
16 attacks (Edvinsson and others 2018), nitric oxide (NO) donors or pituitary adenylate-cyclase
17 activating peptide (PACAP) (Al-Karagholi and others 2019; Ashina and others 2017b; Ashina
18 and others 2017a; De Felice and others 2010; De Felice and Porreca, 2009; Guo and others
19 2016; Liu and others 2013). However, NO donors, for example, are triggers in migraine
20 patients but poorly affect healthy volunteers (Schytz and others 2010). Nevertheless, in
21 certain experimental conditions (doses and combined use of provocative drugs, duration of
22 treatment), a higher proportion of healthy individuals may develop a genuine migraine attack,
23 suggesting the existence of a putative “migraine threshold” (Olesen and Ashina 2015).

24

25 ***Genetic aspects***

26 Early studies on the genetics of migraine have led to the identification of several genes
27 responsible for rare cases of familial hemiplegic migraine (FHM). This includes FHM1, a
28 gain-of-function mutation affecting the alpha subunit of the voltage-gated calcium channel
29 Ca_v2.1 (CACNA1A) leading to an increase in synaptic transmission (van den Maagdenberg
30 and others 2004), FHM2, a loss-of-function mutation targeting the alpha 2 subunit of the
31 astrocytic Na⁺/K⁺ ATP-dependent pump (ATP1A2) and resulting in an impaired clearance of
32 synaptic glutamate (De Fusco and others 2003) and FHM3, impairing the alpha subunit of the
33 voltage-gated sodium channel Na_v1.1 (SCN1A) (Dichgans and others 2005; Zerimech and
34 others 2020). However, those mutations are also linked to other diseases such as dyskinesia,

1 ataxia or mental retardation. Furthermore, they only account to a minor proportion of
2 migraine patients (around 1 of 10000) (Ducros 2013). Another gene whose loss of function
3 has been recently associated with migraine is KCNK18, which encodes the Two-Pore-
4 Domain (K_{2P}) potassium channel TRESK (Twik-related spinal cord K^+ channel) (Lafrenière
5 and others 2010). The mutation in this gene was the only one which has been linked to a
6 “common” migraine phenotype. Nevertheless, the latter was a matter of controversy until
7 recently (Royal and others 2019; Pettingill and others 2019, see below).

8 Due to their contribution to neuronal excitability, a genomic study has explored the
9 potential involvement of hundreds of ion transport genes in migraine pathology (Nyholt and
10 others 2008). However, a significant gene variant has not been identified. In the last years,
11 larger scale genome-wide association studies (GWAS) have made important contributions to
12 identify genetic components involved in migraine, resulting in new hypotheses regarding
13 migraine pathophysiology (Nyholt and others 2017). Further studies provided evidence that
14 common types of migraine are genetically complex: multiple genetic variants with small
15 effect sizes act together with environmental factors to confer migraine susceptibility (Gormley
16 and others 2018). Interestingly, those studies have identified other variants in genes encoding
17 K_{2P} channels, namely KCNK5 (TASK2, Twik-related acid sensing K^+ channel) (Gormley and
18 others 2016) and KCNK4 (TRAAK, Twik-related arachidonic acid stimulated K^+ channel). It
19 is also of note that migraine has a genetic overlap with psychiatric disorders, especially
20 depression, in which K_{2P} channels have been also shown to play a role (Heurteaux and others,
21 2006; Djillani and others 2019).

22

23 [Anatomy - Focus on the migraine pain pathway](#)

24 Multiple sensory symptoms arise during a migraine attack, being the headache the
25 most prominent one. It is now well established that migraine headache is the result of the
26 activation and sensitization (decreasing response threshold and increasing response strengths)
27 of trigeminal neurons and, to a lesser extent, cervical nociceptive C (non-myelinated) and $A\delta$
28 (myelinated) fibers that innervate cranial meninges and their blood vessels (Khan and others
29 2019; Strassman and others 1996). This ensemble is commonly referred to the
30 trigeminovascular system (Fig. 2). The pathway starts in trigeminal sensory neurons whose
31 cell bodies are located in the trigeminal ganglia (TG) and send peripheral axons to the
32 meningeal dura mater and the surrounding blood vessels through the ophthalmic branch of the
33 trigeminal nerve (V1). Central axons from TG neurons project to the trigeminal nucleus
34 caudalis (TNC) (Uddman and others 1985). This nucleus integrates signals from projections

1 coming from periorbital skin and pericranial muscles. The ascending axon projections of TNC
2 transmit nociceptive information to diverse hypothalamic, brainstem and basal ganglia nuclei
3 that could explain different migraine related symptoms such as vomiting, nausea and yawning
4 (Burstein and others 2015). Additionally, trigeminovascular nociceptive information is subject
5 to extensive modulation by multiple descending neurons from different brain regions
6 (Goadsby and others 2017), including various brainstem nuclei, notably the Locus coeruleus
7 and Periaqueductal Grey (Edelmayer and others 2009; Vila-Pueyo and others 2019), the
8 hypothalamus (Goadsby and others 2017) or the cerebral cortex (Nosedá and others 2010).

9 Activation of trigeminal and innervating fibers in meninges is thought to initiate a
10 neurogenic and sterile inflammation, owing to the dense population of various vasoactive
11 neuropeptides (*i.e.* CGRP, PACAP and substance P) within sensory neurons and to the
12 proximity of blood vessels, immune cells (Edvinsson and others 2018; Levy and others 2019;
13 Rua and McGavern 2018) and autonomic neuron fibers (Harriott and Gold 2009). Meningeal
14 sensory neurons are equipped with a rich set of receptors and ion channels, allowing them to
15 be exquisitely sensitive and to respond to a broad range of chemical and mechanical stimuli
16 (Burgos-Vega and others 2016; Levy and others 2019; Bonnet and others 2019). There is now
17 growing evidence that an inflammatory component might sustain nociceptor activation and
18 sensitization, through the action of protons, cytokines or neurotrophic factors and their
19 downstream targets (van Dongen and others 2017).

20 However, the initiating event leading to the activation of meningeal sensory neurons in
21 the context of a migraine attack remains unclear. Regarding migraine with aura, CSD was
22 shown to activate meningeal nociceptors, being also linked to a meningeal inflammation
23 (Bolay and others 2002; Karatas and others 2013; Hadjikhani and others 2020). A more likely
24 explanation combines extensive modulation of trigeminovascular information, predetermined
25 hyperexcitable migraine brain and increase of nociceptive information by external triggering
26 factors (Kunkler and others 2018; Bree and Levy 2018). Nowadays, it is well-established that
27 trigeminal neuron hyperexcitability is a key factor for migraine headache generation and some
28 associated symptoms (throbbing headache, cutaneous allodynia, some autonomic symptoms)
29 through its role in the development of peripheral and central sensitization at various levels of
30 the migraine pain network (Strassman and others 1996; Olesen and others 2009).

32 **K_{2P} channels and pain**

33 K_{2P} channels constitute one of the major families of K⁺ channels. Its members share a
34 dimeric structure with four transmembrane domains and two pore loops per subunit. Because

1 of the two pore loops per subunit, these channels are not active as tetramer but as dimer (Fig.
2 3). K_{2P} channels exhibit a “background” K^+ conductance that is time- and voltage-
3 independent and brings the resting membrane potential of cells toward the K^+ potential
4 equilibrium. Therefore, they serve as a hub for the regulation of neuronal excitability by
5 setting the resting membrane potential below the firing threshold in excitable cells.
6 Furthermore, they were recently shown to contribute to neuronal high firing frequency and
7 high-speed conduction along myelinated axons by driving action potential repolarization
8 (Brohawn and others 2019; Kanda and others 2019; Ávalos Prado and Sandoz 2019). 15
9 genes have been found to encode for this channel family that can be subdivided into six
10 subfamilies depending of their sequence homology and biophysical properties (Box 1). K_{2P}
11 channels play a central and active role in the response of cells to extracellular and intracellular
12 signals as diverse as G-Protein Coupled Receptor (GPCR) signaling, pH and membrane
13 stretch. They have been shown to participate in multiple physiological and pathological
14 aspects of peripheral pain perception. Notably, they have been implicated in thermal and
15 mechanical nociception (Fig. 4, Noël and others 2009) and also in inflammatory, neuropathic,
16 cancer, and recently, migraine pain (Alloui and others 2006; Descoeur and others 2011;
17 Lafrenière and others 2010). This group mainly includes TWIK1, the members of the TREK
18 subfamily (TREK1, TREK2 and TRAAK), the TASK subfamily members (TASK1 and
19 TASK3) and TRESK (Li and Toyoda 2015). They are all expressed throughout the nervous
20 system along the pain pathway in various populations of dorsal root ganglia (DRG) or TG
21 sensory neurons. It is worth to note that they are enriched in small and unmyelinated neurons
22 that are mainly involved in noxious stimuli detection (*e.g.* peptidergic, non-peptidergic, itch
23 or cold-sensitive) (Acosta and others 2014; Alloui and others 2006; Pereira and others 2014).

24

25 K_{2P} channels and migraine

26 With the identification of the FHM genes in the late 90s and in the mid-2000s, a
27 subsequent large-scale study was conducted by Nyholt and colleagues investigating the
28 potential contribution to migraine pathology of common variations affecting several ion
29 transport-related genes. Though none of the studied variants reached a statistical threshold,
30 two K_{2P} channels (TREK1 and THIK2) were preliminarily selected as promising candidates
31 in a Finnish cohort (Nyholt and others 2008). A pioneer study clearly linking K_{2P} channels
32 and migraine led to the identification of a frameshift mutation in the gene encoding for
33 TRESK channel, the F139WfsX24 mutation (TRESK-MT). This mutation, segregating
34 perfectly with migraine with aura phenotype (and sometime without aura), was shown to

1 produce a non-functional protein that served as a dominant-negative form of the wild-type
2 (WT) TRESK channel (Lafrenière and others 2010) explaining its genetic dominant role.
3 TRESK-MT has been shown to induce hyperexcitability of TG neurons (Liu and others 2013;
4 Guo and others 2014), which likely underscores its role in migraine. Furthermore, the
5 causative role of this mutation was emphasized by an elegant study with human nociceptive
6 neurons derived from induced pluripotent stem cells from migraine patients. In fact, these
7 neurons are hyperexcitable and CRISPR-Cas9 engineering, for correcting the F139WfsX24
8 mutation, reversed the neuronal hyperexcitability (Pettingill and others 2019). However, in a
9 subsequent genetic screening study, another missense TRESK variant, C110R, was identified
10 (Andres-Enguix and others 2012). The TRESK-C110R mutation, similarly to TRESK-MT,
11 was shown to produce a non-functional channel which exerts a dominant negative effect on
12 the WT-TRESK channel in heterologous cells, but unexpectedly this mutant was found to
13 have no effect on TG excitability when overexpressed (Guo and others 2014) and in human
14 derived C110R mutant neurons (Pettingill and others 2019). This absence of effect elucidates
15 why this mutant was found in both migraine and control subjects. We have recently shown in
16 rodent that, even though both mutations lead to the same apparent deleterious effect on
17 TRESK function, only TRESK-MT is able to functionally inhibit two other members of the
18 K_{2P} channel family (Fig. 5). Inhibition of TREK1 and TREK2 channels activity then induces
19 TG hyperexcitability and subsequent migraine pathophysiology (Fig. 6) (Royal and others
20 2019; see below).

21

22 ***K_{2P} channels, heteromerization and TG excitability***

23 Even though K_{2P} channels share a low level of sequence identity, it has been recently
24 shown that heteromerization is not rare between K_{2P} members, increasing functional diversity
25 (Levitz and others 2016, Blin and others 2016). Heteroassembly can occur within the same
26 subfamily but also between different subfamily members, as was shown for the dimerization
27 of TRESK with TREK1 and TREK2 in TG neurons (Royal and others 2019). The question,
28 why only TRESK-MT, and not TRESK-C110R leads to an inhibition of TREK1 and TREK2,
29 was solved by the discovery of a new mechanism allowing transmission of inherited diseases
30 through an alternative translation initiation induced by a frameshift mutation in TRESK-MT
31 called frameshift mutation induced Alternative Translation Initiation (fsATI, Box 2; Royal
32 and others 2019).

1 The TRESK-MT mutation leads, through fsATI, to the production of two protein
2 fragments instead of one, as expected (Box 1): TRESK-MT1, which corresponds to the
3 expected C-terminal truncated TRESK channel and inhibits TRESK, and TRESK-MT2,
4 which corresponds to an N-terminal truncated TRESK channel. TRESK-MT2, by co-
5 assembling and inhibiting TREK1 and TREK2, induces TG sensory neuron hyperexcitability
6 (Fig. 5). Overexpression of TRESK-MT2 in rat TG neurons, using virus, is sufficient to
7 induce a chronic facial mechanical allodynia related to chronic migraine, an effect which has
8 not been seen with MT1 (Royal and others 2019). Interestingly, fsATI was also found for
9 another TRESK mutant (Y121LfsX44), which is the only other TRESK mutation related to
10 migraine in human (Royal and others 2019; Domitrz and others 2016; Rainero and others
11 2014). This mutation also leads to the production of a similar TRESK-MT2 (Royal and others
12 2019). The fundamental role of TREK1 and TREK2 in migraine induction has been further
13 supported by TREK1/TREK2 double knock-out (KO) mice (Fig. 5). They exhibit a chronic
14 migraine-like cutaneous mechanical allodynia phenotype which can be reversed by
15 Topiramate, a drug used in clinic to treat migraine (Royal and others 2019). This suggests,
16 that, in human, migraine is due to the dysfunction of TREK1 and TREK2 and their respective
17 heteromers with mutated TRESK, but not due to TRESK invalidation alone (Fig. 6).

18 In parallel, other preclinical studies in rodents have further confirmed a key
19 involvement of K_{2P} channels in trigeminal nociception and migraine-related headache.
20 Recently, TRESK invalidation was shown to increase peptidergic trigeminal neurons
21 excitability (Guo and others 2019) and to enhance headache behavior induced by application
22 of inflammatory mediators in the meninges (Pettingill and others 2019). These results would
23 favor that TRESK is sufficient to generate migraine. Nevertheless, the finding by Guo and
24 others. and Pettingill and others. also fits with TREK1 and TREK2 implication. In fact, by
25 only targeting TRESK, TRESK-MT1 and C110R, the sensory neuron excitability is not
26 altered (Pettingill and others 2019; Guo and others 2014; Royal and others 2019), whereas
27 genetic invalidation affects TRESK homodimers as well as heterodimers (TRESK-TREK1,
28 TRESK-TREK2) and therefore also TREK1 and TREK2 expression and composition at the
29 cell surface (the equilibrium is modified). These differences between gene invalidation and
30 dominant negative (affecting only TRESK) may explain why TRESK invalidation modifies
31 TG excitability and induces a migraine phenotype. All in all, migraine-like behavior in
32 rodents seems to involve both TRESK, TREK1 and TREK2 monomeric channels and
33 TRESK-TREK heterodimeric channels.

1 Finally, in addition to these channels, TASK3 is also predominant in TG neurons,
2 where it co-localizes with TRESK, TREK1 and TREK2 (Yamamoto and others 2009).
3 Nevertheless, there is no evidence of TASK3 participation in migraine attacks. It is worth to
4 mention, that TASK3 was not found to heteromerize with TRESK, TREK1 and TREK2
5 (Levitz and others 2016; Royal and others 2019).

6 7 **Toward new treatments for migraine involving K_{2P} channels targeting**

8 Migraine therapy aims to terminate or to relief acute attacks, but also to prevent the
9 evolution from episodic toward chronic migraine. Several drugs are used but present several
10 side effects (Table1 and 2), for example, Topiramate may be used to treat chronic migraine
11 but it has severe well-known side effects including ataxia, confusion, diplopia, dizziness,
12 drowsiness, dysphasia, fatigue, memory impairment and others. Given the importance of
13 CGRP as a migraine trigger, the use of monoclonal antibodies against this peptide represents
14 one of the most effective treatments against the disease. Up to now, three different humanized
15 monoclonal antibodies against CGRP pathway have been tested and exhibited excellent
16 results: Fremanezumab and Galcanezumab, which target CGPR, and Erenumab, which targets
17 CGRP receptors (Fig. 7). All three products have demonstrated efficacy for the preventive
18 treatment of chronic and episodic migraine and can be periodically self-administered
19 (Spindler and Ryan 2020). In addition, they support the fact that an intervention at the level of
20 the peripheral nervous system is sufficient to target migraine headache. Nevertheless, general
21 side effects caused by monoclonal antibody drugs cannot be excluded such as flu-like
22 symptoms and allergic reactions in addition to the “specific” side effects such as dizziness,
23 joint pain or pruritus and erythema.

24 Given their abundant expression in DRG, TG sensory and primary afferent neurons,
25 drugs targeting K_{2P} channels constitute a promising therapy for the treatment of migraine and
26 its associated pain, but also of inflammatory, neuropathic or cancer pains (Pereira and others
27 2014; Noël and others 2009; Alloui and others 2006; Descoeur and others 2011). This idea is
28 strengthened by the fact that K_{2P} channels have been shown to be involved in other diseases
29 such as depression (Heurteaux and others 2006) which severely affect 10% of the population
30 suffering from migraine disorders, and that some drugs targeting K_{2P} channels have been
31 proved to be effective against migraine, such as cloxyquin through TRESK activation
32 (Pettingill and others 2019).

1 As previously shown, at least three K_{2P} channels subunits and their respective
2 heteromers have been proved to be involved in the normal physiology and pathophysiology of
3 migraine. TRESK, TREK1 and TREK2 containing channels seem to serve as a hub to set the
4 negative resting potential of TG neurons (Dobler and others 2007; Lafrenière and others 2010;
5 Royal and others 2019). Thus, specific pharmacology targeting these channels should be
6 potentially relevant for the development of anti-migraine treatment. Furthermore, targeting
7 heterodimers would allow to reach higher specificity. Currently, only a small number of
8 agonists of the aforementioned channels have been studied to be effective for migraine
9 treatment. Among them, the anti-leukotriene agent Montelukast for asthma management has
10 been demonstrated to act as a well-tolerated and prophylactic agent against acute migraine
11 episodes at 10-20 mg dose per day (Sheftell and others 2000). Its efficacy may lie in its ability
12 to specifically activate TRESK and TRESK heteromer channels (Wright and others 2019).

13 During migraine, experimental studies have demonstrated an increase of prostaglandin
14 2 (PGE2) in the trigeminovascular system, where their receptors are distributed along TG and
15 TNC neurons and induce vasodilation of cranial vessels (Antonova and others 2013). PGE2 is
16 also known to be a potent inhibitor of TREK1 channels (Honoré 2007). Non-steroidal anti-
17 inflammatory drugs (NSAIDs), which represent another widespread treatment to manage
18 headache in acute migraine, may eventually avoid TREK1 inhibition.

19 Finally, although they have not yet been clinically tested, a number of selective
20 activators of K_{2P} channels should also be considered for chronic migraine prevention. Among
21 them, it is worth to mention ML67-33, a well-known specific activator of TREK1, TREK2
22 and TRAAK channels, that exhibit an EC_{50} in micromolar range (Bagriantsev and others
23 2013). Further development of selective agents targeting specific heterodimers involving
24 TRESK may be considered to increase specificity and to reduce secondary drug effects.

25

26 [Concluding remarks](#)

27 Migraine is a common and disabling disease associated with disorders in neuronal
28 excitability and cerebral blood flow. The complexity of the underlying processes which are
29 not yet fully understood still render migraine treatment difficult. Currently, it is assumed that
30 migraine headache is triggered by TG neuron activation. Hyperexcitability of TG fibers
31 evokes release of vasoactive neuropeptides that enhance vasodilation causing neurogenic
32 inflammation. This leads to a pain response to be conveyed to higher brain centers including
33 cortex, hypothalamic, brainstem and basal ganglia nuclei. The mechanisms leading to
34 trigeminal hyperexcitability have not been fully elucidated until very recently.

1 K_{2P} channels, namely homo- and heterodimers of TRESK, TREK1 and TREK2, seem
2 to play a key role in TG neuronal excitability and are therefore promising targets for migraine
3 treatment. The discovery of a new type of translation initiation, generating several protein
4 forms that can regulate other channels by heteromerization, clarified the understanding of K_{2P}
5 channel implication in this disease. Henceforth, the novel role of K_{2P} channels in migraine, as
6 well as their ability to generate functional and non-functional heterodimers, provides
7 motivation for developing a deeper understanding of their function and organization within
8 the plasma membrane and demonstrates that they have to be now taken into consideration for
9 the development of highly specific pharmacological agents to treat migraine.

10

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20

1 **Table 1. Current preventive treatments of migraine, their targets and the proposed**
 2 **mechanism of action.**

Preventive treatment	Targets	Mechanism of action
Beta blockers (Propranolol)	β 1-2 receptor antagonist	Stress reduction, neuronal modulation (descending controls), vascular effects?
Antiepileptics (Valproate, Topiramate, Levetiracetam, Flunarizine, Gabapentine)	Valproate: Na _v antagonist	Decrease in neuronal excitation
	Topiramate: acts on Na _v , Ca _v and carbonic anhydrase, modulates GABA-A and kainate receptors	Decrease in neuronal excitation
	Levetiracetam: acts on SV2A (vesicular protein), Ca _v	Decrease in neuronal excitation, modulation of neuronal activity
	Flunarizine: calmodulin blocker, H1R, 5HTR and D2R antagonist	Reduces neuronal excitation, modulation of neuronal activity?
	Gabapentine: Ca _v (α 2 δ) antagonist	Reduces neuronal excitation
Antidepressors (tricyclic: Amitriptyline, SNRIs: Venlafaxine)	Amitriptyline: prevents monoamine reuptake, multiple potential secondary targets (5HTR, H1-2R, α 1R, Ca _v , Na _v , K _v etc.)	Multiple actions: Decrease in neuronal excitation, modulation of neuronal activity
	Venlafaxine: prevents monoamine reuptake	Modulation of neuronal activity?
5HTR antagonists (Pizotifen, Methysergide)	5HT2R antagonists	Modulation of neuronal activity?
Botulinum toxin	Exocytosis of neurotransmitter vesicle	Multiple actions: muscle contraction, neuronal modulation (TRP trafficking, synaptic transmission)?
ACE inhibitors (Lisinopril, Candesartan)	Lisinopril: ACE blocker (reduces production of angiotensine II)	Multiple actions: Modulation of neuronal activity (autonomic and sensory), vascular?
	Candesartan: AT1R antagonist	
Anti-CGRP (Erenumab, Fremanezumab)	Erenumab: antibody directed against CGRP receptor	Modulation of neuronal function (neurotransmission, neuromodulation)

	Fremanezumab: antibody against CGRP peptide	
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1

2

3 **Table 2. Current treatments of acute migraine, their targets and the proposed**
 4 **mechanism of action.**

Acute treatment	Targets	Mechanism of action
First line analgesics (Paracetamol, NSAID)	Paracetamol: multiple targets (modulation of K _v 7, TRPV1, Ca _v 3.2, COXs...)	Multiple actions: Decrease in neuronal excitation, modulation of neuronal activity?
	NSAID: inhibition COXs	Reduction of the production of inflammatory molecules (prostaglandines etc.)
Triptans (Sumatriptan)	5HT1B/5HT1D agonists	Modulation of neuronal function, other cells (vascular for 5HT1B)?
Dihydroergotamine	5HT1B/5HT1D agonists	Like Triptans, with a potential central and vascular action
CGRP antagonists (Rimegepant, Ubrogepant)	CGRP receptor antagonist	Modulation of neuronal function (neurotransmission, neuromodulation)
Ditans (Lasmiditan)	5HT1F/5HT1D agonist	Modulation of neuronal function (neurotransmission, neuromodulation)

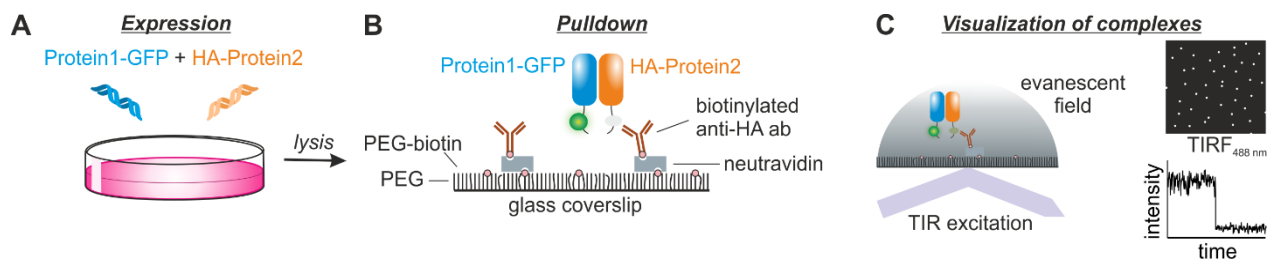
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6

1 Box I – Ion channel heteromerization and means to study it

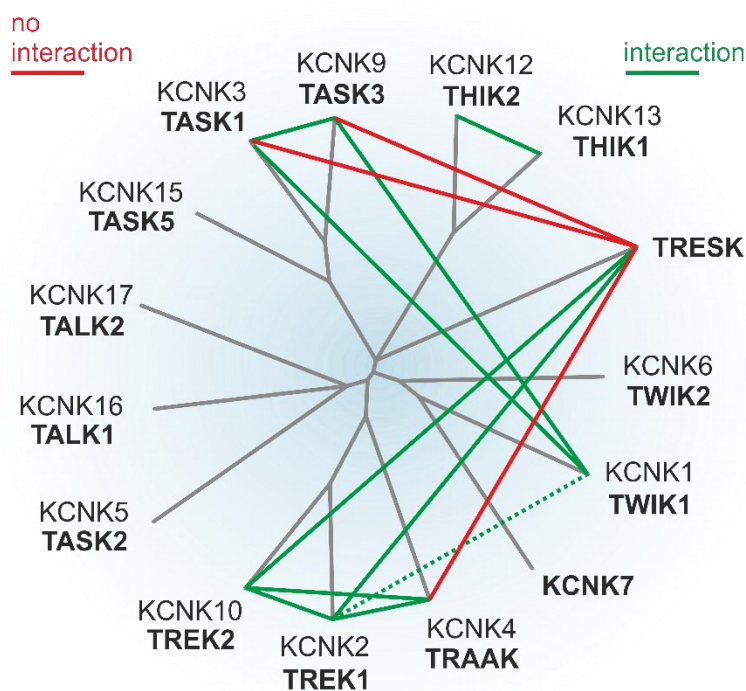
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3 Heteromultimerization is a classical mechanism commonly used to increase the
4 diversity of protein complexes. Despite the fact that K_{2P} channels share rather low sequence
5 identity, it has been demonstrated that heteromerization is possible between different K_{2P}
6 members. The first hints that pointed to the general possibility of a heteroassembly of K_{2P}
7 members were reported in 2002 (Czirják and Enyedi 2002) when co-expression of TASK1
8 and TASK3 in *Xenopus* oocytes led to functional channels with intermediate channel
9 properties. After, the existence of native TASK1/TASK3 dimers was proven in mammalian
10 motoneurons (Berg and others 2004). Later, it was shown that these channels also dimerize
11 with a member of a different subfamily, namely TWIK1 (Plant and others 2012), and several
12 studies reported potential dimers of TWIK1/TREK1 (Mi Hwang and others 2014),
13 THIK1/THIK2 (Blin and others 2014), TREK1/TREK2/TRAAK (Blin and others 2016;
14 Levitz and others 2016), TASK1/TALK2 (Suzuki and others 2017) and finally,
15 TREK1/TREK2/TRESK (Royal and others 2019). Nevertheless, not all K_{2P} subunits of the
16 K_{2P} family are able to dimerize to form functional channels, but the compilation of a full K_{2P}
17 interactome is impeded by the great variety of channel properties as well as the absence of
18 specific pharmacology. The toolbox to study K_{2P} channel dimerization ranges from
19 electrophysiology recordings of co-expressed or tandem-linked channels to fluorescence
20 resonance energy transfer (FRET) assays or fluorescence imaging of co-localization
21 experiments. The use of such various technical approaches has led to controversies in the
22 field, for example for the TREK1-TWIK1 dimers, which has been described as the main
23 potassium conductance in astrocytes (Hwang and others 2014), whereas this dimer was shown
24 not to exist in a previous study (Plant 2012). To address the question of protein assembly, a
25 new technology allowing direct visualization at single molecule level has been developed, the
26 so-called Single Molecule Pulldown (SiMPull) assay (Jain and others 2011), based on
27 antibody-mediated immunoprecipitation of protein subunits carrying an affinity tag (*e.g.* HA)
28 on passivated coverslips (Fig. B1-1). These proteins serve as bait molecules which can
29 capture their respective fluorescence tagged protein partners. The visualization of this
30 interaction is then carried out by total internal fluorescence (TIRF) microscopy. The
31 combination of biochemical immunoprecipitation with single molecule fluorescence
32 microscopy allows to systematically test all K_{2P} interactions among the 120 that can be
33 expected from the combination of the 15 members of the K_{2P} channel family (Fig. B1-2).



1

2 **Figure B1-1:** Principle of the Single Molecule Pulldown assay. (A) To study the interaction of
 3 two proteins of interest, a protein with a fluorescence tag like the green fluorescent protein
 4 (GFP) is co-expressed with a second protein exhibiting an affinity tag like HA. (B) After lysis
 5 of the cells, the lysate is applied in flow chambers on passivated coverslips containing surface
 6 tethered antibodies. (C) The presence of GFP-tagged proteins allows the visualization of
 7 single protein complexes by TIRF microscopy and subunit counting by observation of
 8 bleaching events.



9

10 **Figure B1-2:** Interactome study of K_{2P} channels in TG neurons. Green lines indicate a
 11 confirmed interaction between the respective subunits, while red lines connect subunits which
 12 are not interacting. The dotted line indicates the controversial interaction between *TREK1*
 13 and *TWIK1*.

14

1 Box 2 - Frameshift-mutation induced alternative translation initiation

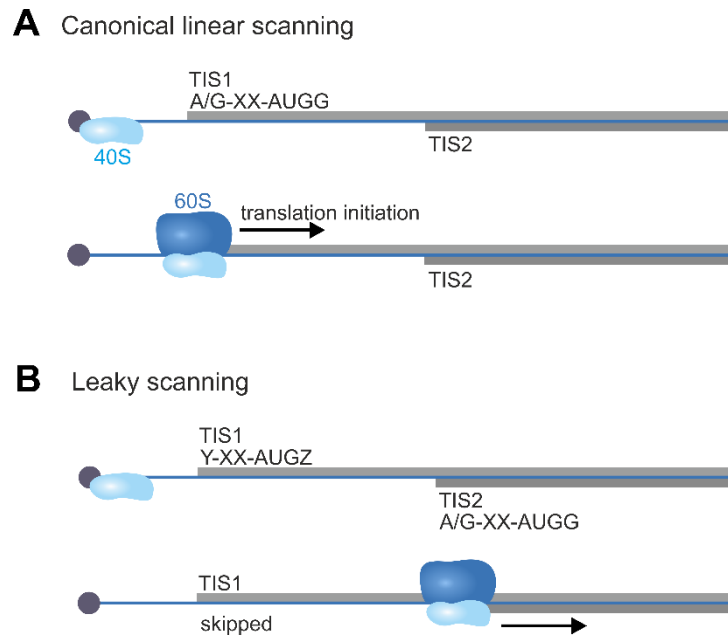
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3 The TRESK-MT mutation, induced by the frameshift F139WfsX24, is expected to
4 encode for a non-functional channel, as it is truncated by its C-terminal part. The WT-TRESK
5 channel was shown to interact with TREK1 and TREK2 in SiMPull assays, whereas the
6 TRESK-MT channel was not (Royal and others 2019). If the inhibition of the TREK1/2
7 current by co-expression of TRESK-MT had not its origin in a co-assembly with this
8 truncated channel form, there must be another explanation.

9 It has been assumed for a long time that one eukaryotic mRNA leads to the production
10 of one single protein and that the variety of protein isoforms derived from one gene is evoked
11 by alternative splicing or transcription from alternative promoters. The dogma of the existence
12 of a unique translation start site was rebutted by Marilyn Kozak, who described that in certain
13 cases, the rule of one mRNA - one protein is not followed as strictly (Kozak 1999). In fact,
14 ribosomes can recognize an alternative initiation site and induce the generation of a second
15 protein coming from the same RNA.

16 The canonical translation usually starts by binding of the 40S ribosomal subunit,
17 initiator tRNA and several initiating factors (*e.g.* eIF4E) at the 5' cap structure, a 7-
18 methylguanosine (m^7G) which precedes all eukaryotic mRNAs. The formation of this so-
19 called pre-initiation complex is followed by linear scanning of the mRNA for an AUG
20 initiation codon that is located in the right context which is in most eukaryotic mRNAs given
21 by the Kozak sequence (A/G-XX-ATGG (Kozak 1987). Subsequent binding of the 60S
22 ribosomal subunit to the translation initiation site (TIS) then initiates the protein translation.
23 However, if the context of the first AUG on the mRNA is not optimal (*i.e.* not fully matching
24 the Kozak sequence), the codon might be skipped, and the translation will start at a
25 downstream AUG which has a more optimal context. This mechanism is also referred to as
26 leaky scanning (Kochetov, 2008).

27 Such mechanism increases the diversity of proteins derived from one gene and has
28 been already nicely described for K_{2P} channels in 2008 (Thomas and others 2008). In this
29 study, an alternative translation initiation site in the TREK1 channel expressed in rat brain has
30 been found to lead to a second truncated channel isoform missing the first 56 amino acids.
31 This $\Delta 1-56$ TREK1 channel is able to form functional homodimers as pseudo-heterodimers
32 with the full-length protein which leads to various channel isoforms with alternate open
33 probability, conductance and permeability properties. Here, the second AUG was embedded

1 in a stronger Kozak sequence which is recognized more efficiently as the first AUG. The
2 study impressively demonstrated, how leaky scanning of ion channel genes like KCNK2 can
3 effectively contribute to the regulation of CNS excitability.



4

5 **Figure B2-1:** Two common examples of eukaryotic translation initiation. (A) In the linear
6 scanning model, the 40S ribosomal subunit binds to the 5' m^7G cap followed by subsequent
7 scanning of the mRNA for an AUG codon, ideally embedded in a Kozak sequence (A/G-XX-
8 AUGG), which serves as TIS. After assembly with the 60S ribosomal subunit, translation is
9 initiated. (B) If the first scanned AUG is embedded in a suboptimal Kozak sequence (Y-XX-
10 AUGZ, Y and Z representing Kozak-deviant bases), it is not efficiently recognized, and the
11 scanning will proceed until the next suitable TIS is detected.

12 In the case of the KCNK18 gene encoding for TRESK, a second AUG in a strong
13 Kozak context can be found at position +356, yet ahead of a very short open-reading frame
14 (ORF2). The frameshift in TRESK-MT, which is induced by deletion of two base pairs
15 (c.410_411delCT), puts the AUG of ORF2 in frame with the C-terminal part of the full length
16 TRESK. As the AUG of ORF2 is also embedded in an environment matching the Kozak
17 sequence, the frameshift leads to the efficient translation of a second protein that corresponds
18 to a TRESK-channel truncated by its N-terminus and therefore, non-functional (TRESK-
19 MT2). The existence of this second transcript was elicited by several cell biological and
20 biochemical assays (Royal and others 2019). We named the newly described mechanism,
21 which is inducing an alternative translation site by displacing the open reading frame, fsATI
22 (frameshift-mutation induced alternative translation initiation).

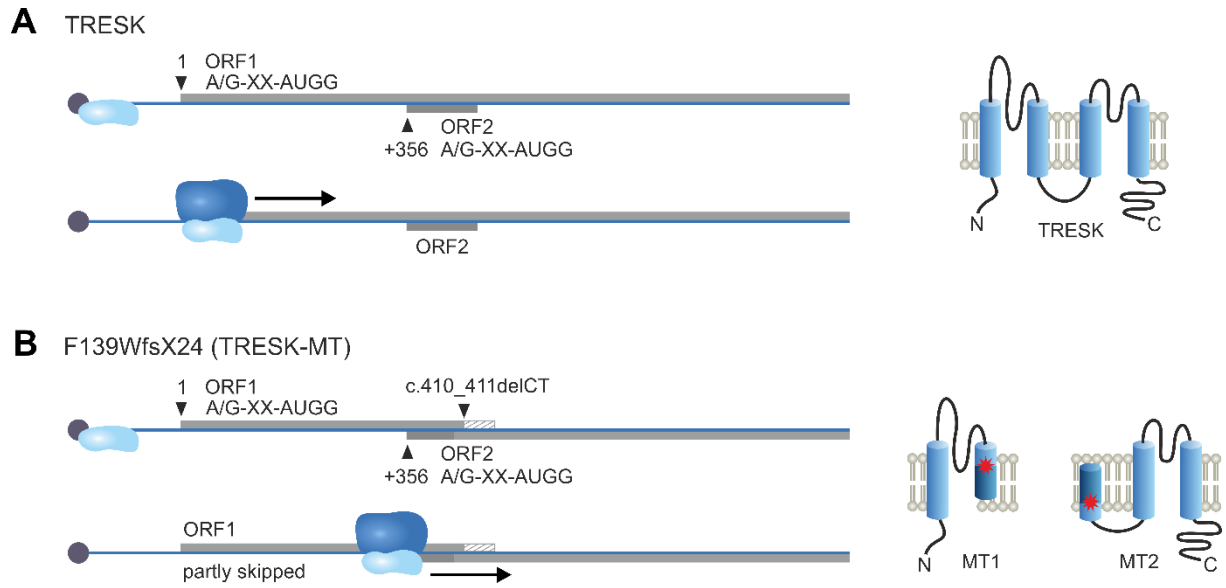
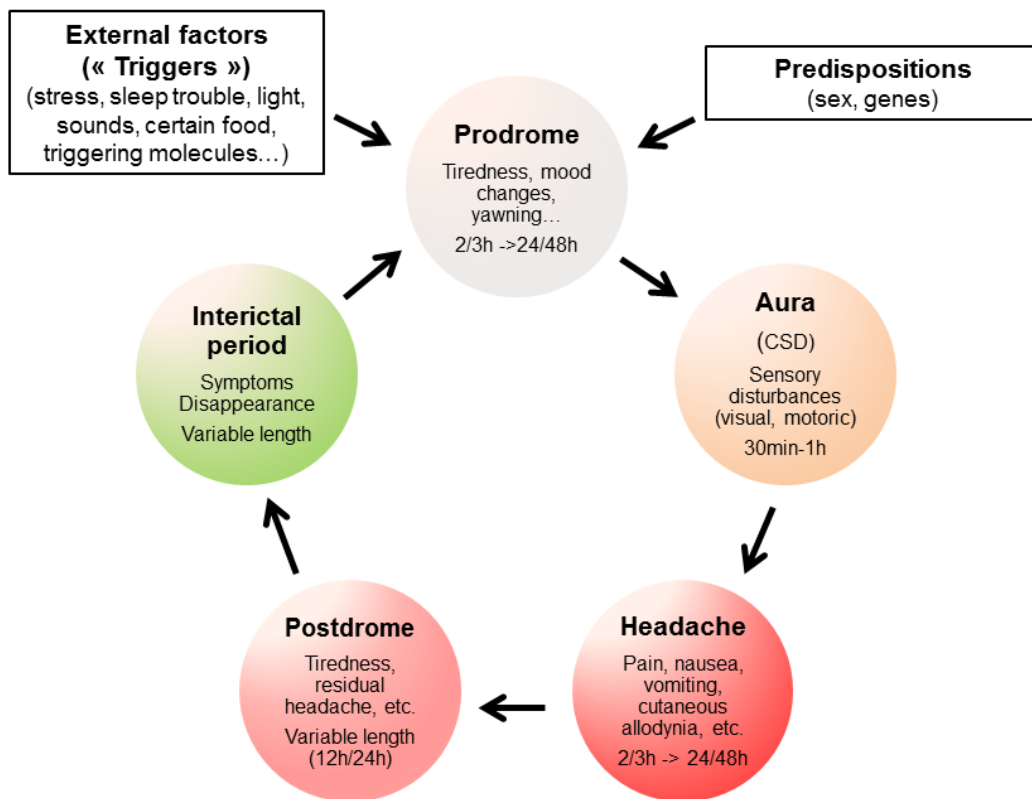


Figure B2-2: Principle of the frameshift-induced alternative translation initiation. (A) Organization of ORF1 and ORF2 on mRNA of WT-TRESK. (B) The deletion of two base pairs by the c.410_411delCT mutation results to a premature translation stop in ORF1(TRESK-MT1). Coincidentally, the start codon of ORF2 at +356 is put in frame with the ORF of TRESK, inducing the translation of MT2.

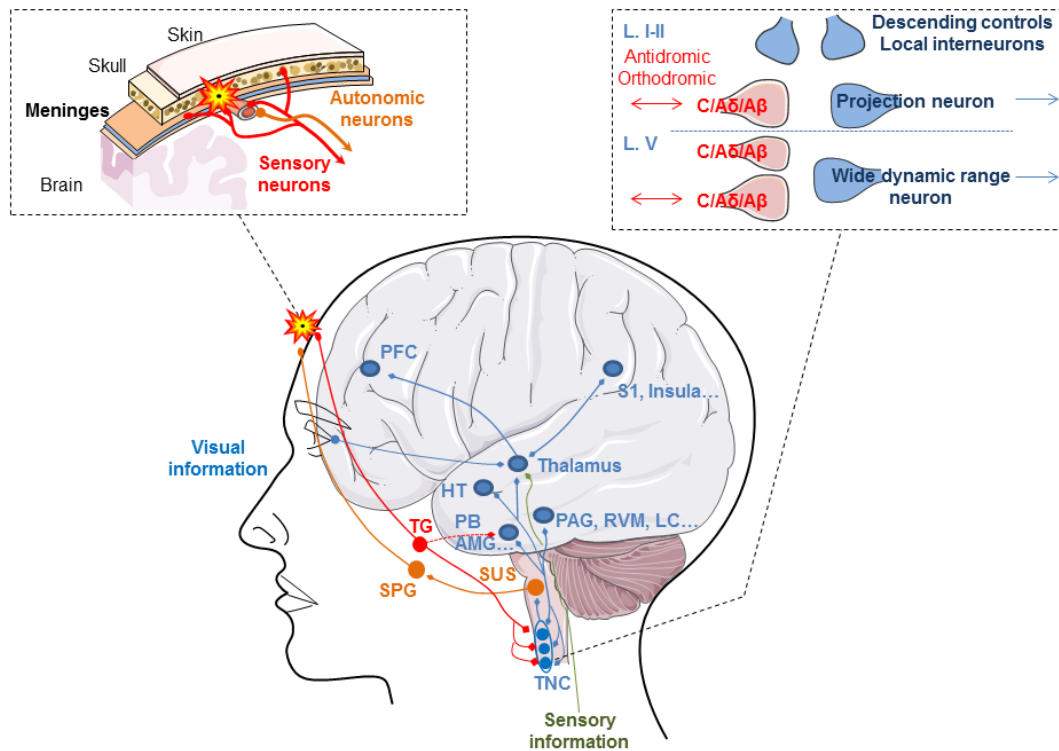
1 **Figures**



2

3 **Figure 1. Schematic display of the migraine crisis and its associated symptoms.** A
4 combination of external factors and predispositions are underlying the generation of a
5 migraine attack. The different phases (red circles) have variable length and are characterized
6 by multiple, sometimes overlapping symptoms. The interictal period (green circle)
7 corresponds to the end of migraine-associated symptoms. The duration of this phase is
8 variable and will depend on many factors such as medication overuse or inappropriate
9 behavior leading to a longer exposure to potential triggering factors. As such, chronic
10 migraine patients have a considerably reduced interictal period.

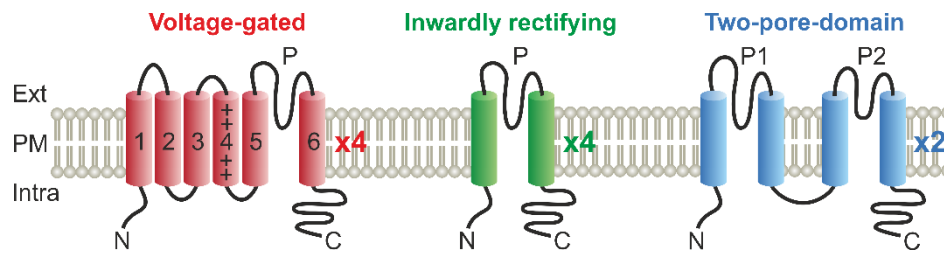
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2 **Figure 2. Migraine pathophysiology: Anatomy of the trigeminovascular pathway.** The
 3 migraine attack begins in trigeminal ganglion (TG), whose axons (red lines) project to
 4 meningeal dura mater blood vessels through the ophthalmic branch stimulating the
 5 production of vasoactive neuropeptides. Nociceptive information is then carried from
 6 meninges to the rest of the brain through sensory and autonomic neurons. A second group of
 7 axons from TG targets the trigeminal nucleus caudalis (TNC), which also receives
 8 information from anterior and posterior parts of head and upper neck (red lines). TNC
 9 conveys then the inputs to diverse nuclei at limbic system, basal ganglia, hypothalamus,
 10 cortex and thalamus (blue lines). The thalamus also integrates stimuli detected from the
 11 outside and from internal organs (green lines). Additional nuclei are believed to contribute to
 12 migraine headache. Activation of the sphenopalatine ganglion (SPG) (orange lines) may
 13 stimulate antidromic sensory fibers converging to the superior salivatory nucleus (SUS),
 14 which contains cell bodies involved in the parasympathetic autonomic vasodilator pathway.

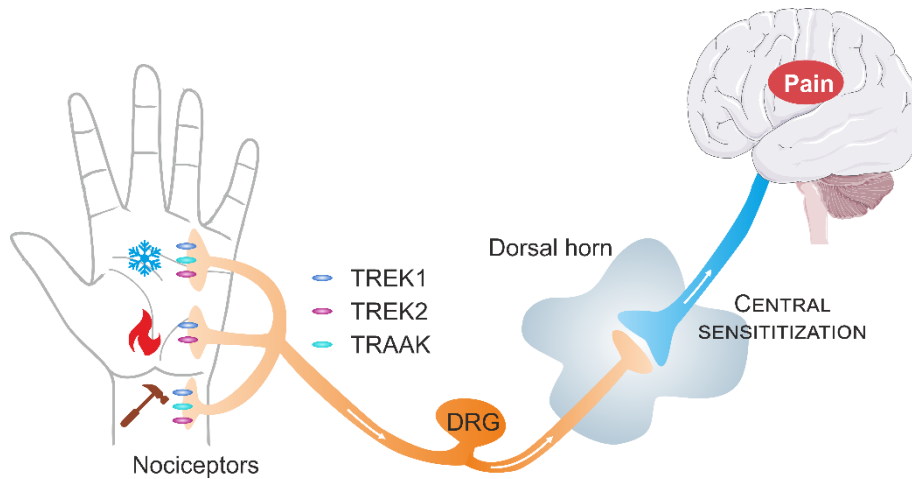
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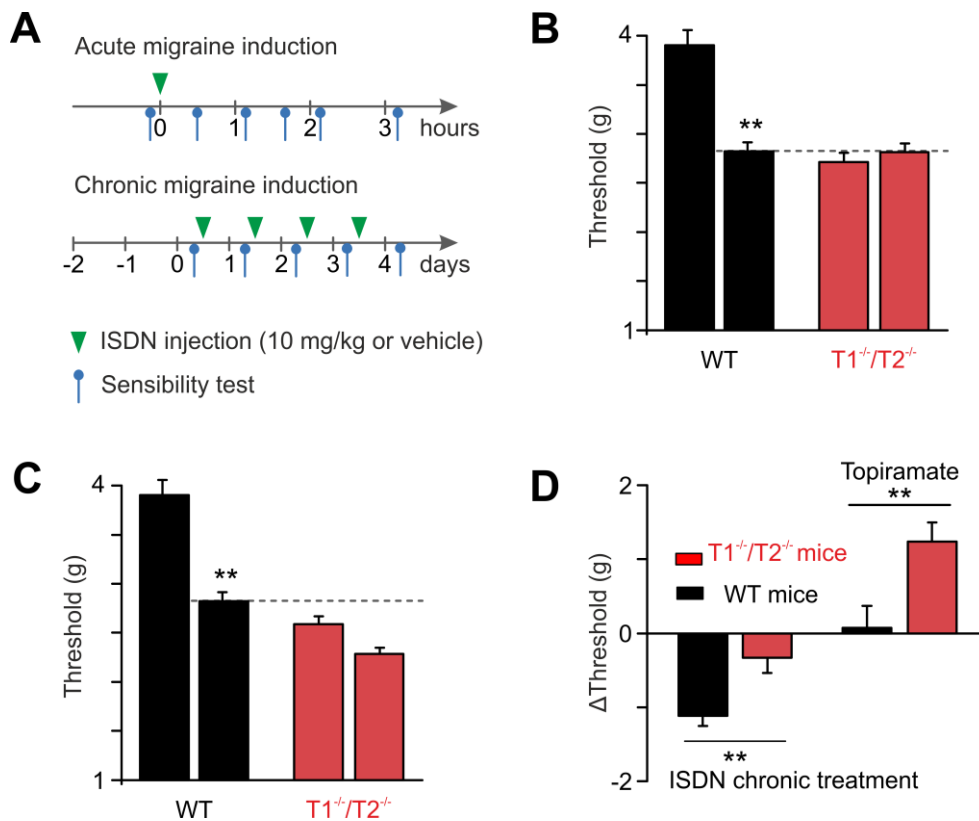
2 **Figure 3. Membrane topology of Potassium channels.** Voltage-gated channels (red) possess
 3 six transmembrane domains and one pore domain (P). Some of them also present a seventh
 4 transmembrane segment. The inward rectifier channels (green) consist of two transmembrane
 5 domains and one pore domain (P), like the voltage-dependent channels they are active as
 6 tetramers. The two-pore-domain potassium channels (blue) possess four transmembrane
 7 domains and two pore domains (P1 and P2) and are active as dimers.

8



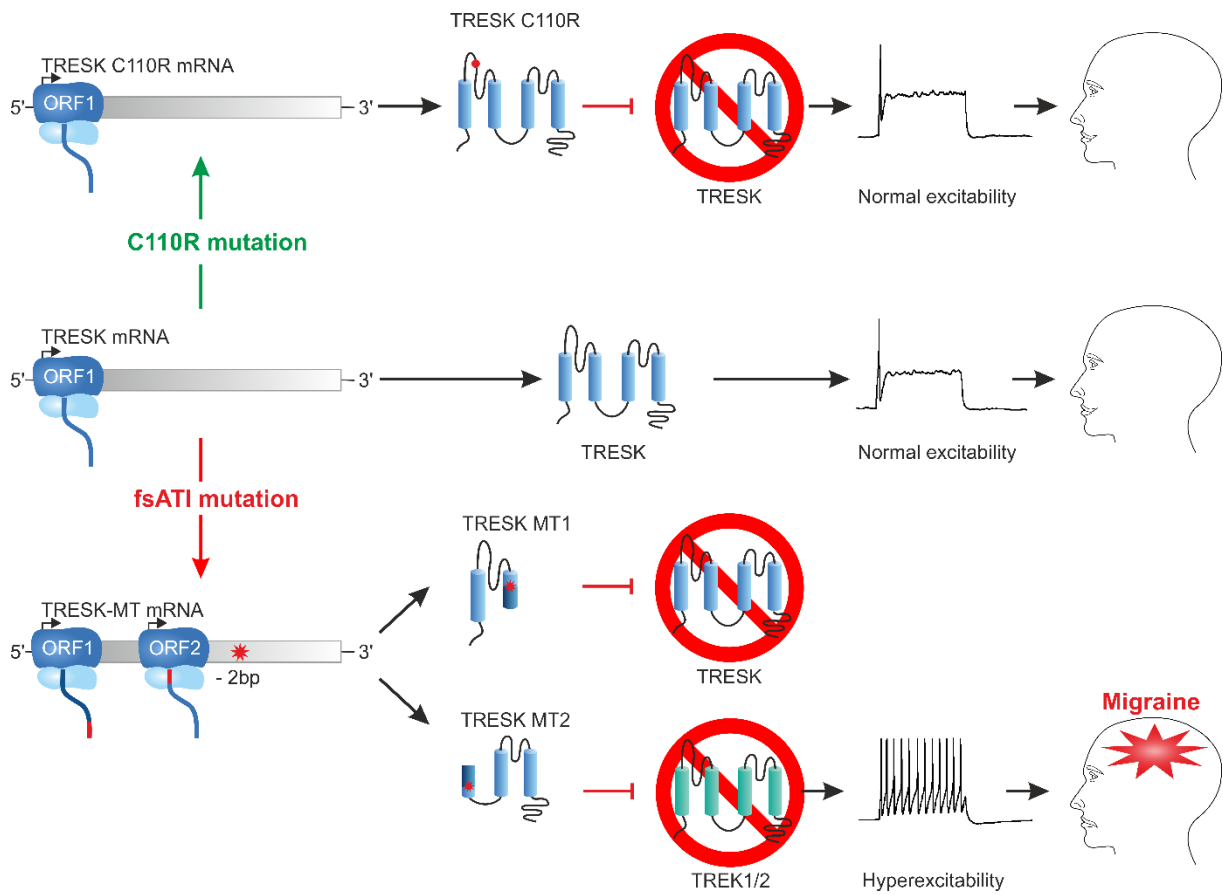
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2 **Figure 4. TREK channel members are involved in several polymodal ways of pain**
 3 **perception.** Thermal and mechanical stimuli are detected by several TREK channels
 4 expressed in nociceptors (along with other ASIC, TRP and piezo channels...). They are
 5 primary sensors of a nervous signal that is sent to the cortex where it is integrated as a pain
 6 signal. DRG for dorsal root ganglion.



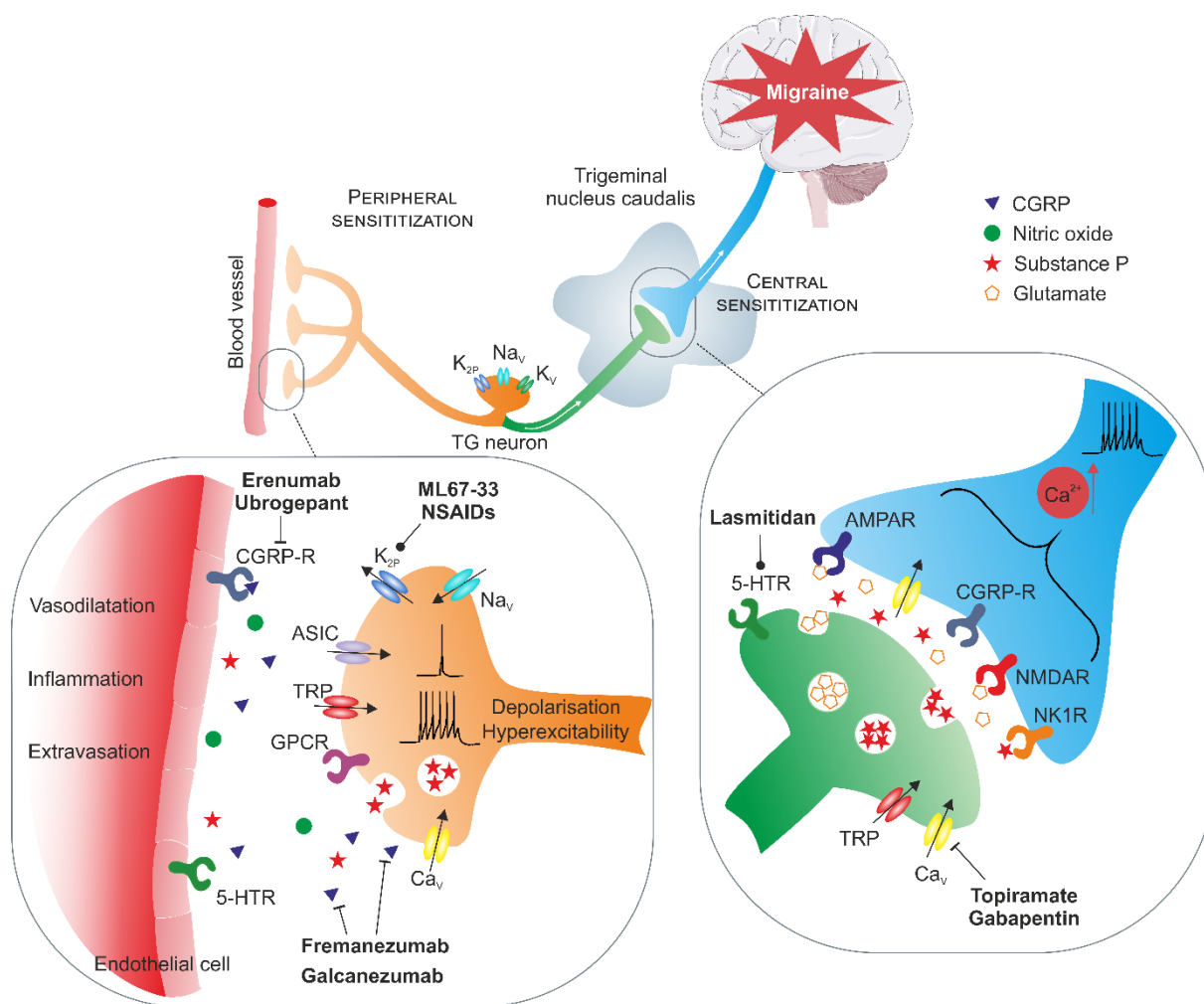
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2

3 **Figure 5. *TREK1*^{-/-}/*TREK2*^{-/-} double knockout animals present a migraine-like phenotype.**
 4 (A) Schematic of experimental behavioral paradigms. Green arrows represent the injection of
 5 ISDN, an established migraine trigger. Blue arrows represent measurements of mechanical
 6 sensitivity. (B) Bar graph representing the paw withdrawal mechanical thresholds assessed
 7 1.5 hours after ISDN injection. The WT mice present a significant decreased paw withdrawal,
 8 whereas no modification was observed for double knockout animals (*T1*^{-/-}/*T2*^{-/-}). (C)
 9 Mechanical responses, assessed prior to and after chronic ISDN injection (4 days), were
 10 significantly decreased in WT animals, whereas no significant change of allodynia was
 11 observed in *T1*^{-/-}/*T2*^{-/-} animals. (D) Variation Δ Threshold (g) of the paw withdrawal
 12 mechanical threshold induced by ISDN chronic treatment or topiramate injection.
 13 Mechanical responses were assessed before and after chronic ISDN treatment (4 days, left
 14 bars), and before and two hours after topiramate injection (right bars) in ISDN-non treated
 15 WT and *T1*^{-/-}/*T2*^{-/-} mice (from Royal and others 2019).



1
2

3 **Figure 6: TRESK-MT causes migraine via inhibition of TREK1 and TREK2 by TRESK-**
 4 **MT2.** Top: TRESKC110R targets only TRESK, which is not sufficient to induce an increase of
 5 trigeminal sensory neuron excitability and therefore does lead to migraine. Middle: the
 6 excitability of trigeminal neurons in the presence of the wild version of TRESK is normal.
 7 Bottom: the TRESK-MT mutation generates an ATI (see Box1) resulting in the formation of
 8 two proteins, TRESK-MT1 and TRESK-MT2. TRESK-MT1 inhibits TRESK, while TRESK-
 9 MT2 targets TREK1 and TREK2. Inhibition of TREK1 and TREK2 leads to neuronal
 10 hyperexcitability causing a migraine phenotype.



1
 2 **Figure 7. Main targets of currently used and potential future drugs for treating migraine**
 3 **headache.** The analgesic action is mainly exerted by influencing several classes of receptors
 4 (ion channels, GPCRs etc.) at multiple levels of the migraine pain pathway (peripheral
 5 trigeminal sensory neurons, TNC second order and higher neurons in the brain). They are
 6 principally acting on the neuronal hyperexcitability and the sensitization associated to
 7 migraine headache. Multiple drugs will aim at limiting the excessive depolarization through
 8 the blockade of inward cation flux (e.g antiepileptics) or, on the opposite, through the
 9 activation of hyperpolarizing potassium channels (e.g potential K_{2P} agonists). Other classes
 10 act on the neuronal modulation (e.g CGRP antibodies) or neurotransmitters release (e.g
 11 Triptans).

1 References and notes

2

- 3 Acosta C, Djouhri L, Watkins R, Berry C, Bromage K, Lawson SN. 2014. TREK2 expressed selectively in
4 IB4-binding C-fiber nociceptors hyperpolarizes their membrane potentials and limits
5 spontaneous pain. *J Neurosci* 34(4):1494-509.
- 6 Adams AM, Serrano D, Buse DC, Reed ML, Marske V, Fanning KM and others. 2015. The impact of
7 chronic migraine: The Chronic Migraine Epidemiology and Outcomes (CaMEO) Study
8 methods and baseline results. *Cephalgia* 35(7):563-78.
- 9 Al-Karagholi MA, Hansen JM, Guo S, Olesen J, Ashina M. 2019. Opening of ATP-sensitive potassium
10 channels causes migraine attacks: a new target for the treatment of migraine. *Brain*
11 142(9):2644-2654.
- 12 Alloui A, Zimmermann K, Mamet J, Duprat F, Noël J, Chemin J and others. 2006. TREK-1, a K⁺ channel
13 involved in polymodal pain perception. *EMBO J* 25(11):2368-76.
- 14 Andres-Enguix I, Shang L, Stansfeld PJ, Morahan JM, Sansom MS, Lafrenière RG and others. 2012.
15 Functional analysis of missense variants in the TRESK (KCNK18) K channel. *Sci Rep* 2:237.
- 16 Antonova M, Wienecke T, Olesen J, Ashina M. 2013. Prostaglandins in migraine: update. *Curr Opin*
17 *Neurol* 26(3):269-75.
- 18 Ashina M, Dodick D, Goadsby PJ, Reuter U, Silberstein S, Zhang F and others. 2017. Erenumab (AMG
19 334) in episodic migraine: Interim analysis of an ongoing open-label study. *Neurology*
20 89(12):1237-1243.
- 21 Ashina M, Hansen JM, Á Dunga BO, Olesen J. 2017. Human models of migraine - short-term pain for
22 long-term gain. *Nat Rev Neurol* 13(12):713-724.
- 23 Ávalos Prado P, Sandoz G. 2019. TREK for High-Speed and High-Frequency Conduction through the
24 Axon. *Neuron* 104(5):831-833.
- 25 Bagriantsev SN, Ang KH, Gallardo-Godoy A, Clark KA, Arkin MR, Renslo AR and others. 2013. A high-
26 throughput functional screen identifies small molecule regulators of temperature- and
27 mechano-sensitive K₂P channels. *ACS Chem Biol* 8(8):1841-51.
- 28 Berg AP, Talley EM, Manger JP, Bayliss DA. 2004. Motoneurons express heteromeric TWIK-related
29 acid-sensitive K⁺ (TASK) channels containing TASK-1 (KCNK3) and TASK-3 (KCNK9) subunits.
30 *The Journal of neuroscience : the official journal of the Society for Neuroscience* 24(30):6693-
31 6702.
- 32 Bernstein CA, Nir RR, Nosedá R, Fulton AB, Huntington S, Lee AJ and others. 2019. The migraine eye:
33 distinct rod-driven retinal pathways' response to dim light challenges the visual cortex
34 hyperexcitability theory. *Pain* 160(3):569-578.
- 35 Blin S, Ben Soussia I, Kim E-J, Brau F, Kang D, Lesage F and others. 2016. Mixing and matching
36 TREK/TRAAK subunits generate heterodimeric K₂P channels with unique
37 properties. *Proceedings of the National Academy of Sciences* 113(15):4200.
- 38 Blin S, Chatelain FC, Feliciangeli S, Kang D, Lesage F, Bichet D. 2014. Tandem pore domain halothane-
39 inhibited K⁺ channel subunits THIK1 and THIK2 assemble and form active channels. *The*
40 *Journal of biological chemistry* 289(41):28202-28212.
- 41 Bolay H, Reuter U, Dunn AK, Huang Z, Boas DA, Moskowitz MA. 2002. Intrinsic brain activity triggers
42 trigeminal meningeal afferents in a migraine model. *Nat Med* 8(2):136-42.
- 43 Bonnet C, Hao J, Osorio N, Donnet A, Penalba V, Ruel J and others. 2019. Maladaptive activation of
44 Nav1.9 channels by nitric oxide causes triptan-induced medication overuse headache. *Nat*
45 *Commun* 10(1):4253.
- 46 Borsook D, Maleki N, Becerra L, McEwen B. 2012. Understanding migraine through the lens of
47 maladaptive stress responses: a model disease of allostatic load. *Neuron* 73(2):219-34.
- 48 Bose P, Karsan N, Goadsby PJ. 2018. The Migraine Postdrome. *Continuum (Minneapolis, Minn)* 24(4,
49 *Headache*):1023-1031.

- 1 Bree D, Levy D. 2018. Development of CGRP-dependent pain and headache related behaviours in a
2 rat model of concussion: Implications for mechanisms of post-traumatic headache.
3 *Cephalalgia* 38(2):246-258.
- 4 Brohawn SG, Wang W, Handler A, Campbell EB, Schwarz JR, MacKinnon R. 2019. The
5 mechanosensitive ion channel TRAAK is localized to the mammalian node of Ranvier. *Elife* 8.
- 6 Burch RC, Loder S, Loder E, Smitherman TA. 2015. The prevalence and burden of migraine and severe
7 headache in the United States: updated statistics from government health surveillance
8 studies. *Headache* 55(1):21-34.
- 9 Burgos-Vega CC, Ahn DD, Bischoff C, Wang W, Horne D, Wang J and others. 2016. Meningeal
10 transient receptor potential channel M8 activation causes cutaneous facial and hindpaw
11 allodynia in a preclinical rodent model of headache. *Cephalalgia* 36(2):185-93.
- 12 Burstein R, Nosedá R, Borsook D. 2015. Migraine: multiple processes, complex pathophysiology. *J*
13 *Neurosci* 35(17):6619-29.
- 14 Castellanos A, Andres A, Bernal L, Callejo G, Comes N, Gual A and others. 2018. Pyrethroids inhibit
15 K2P channels and activate sensory neurons: basis of insecticide-induced paraesthesias. *Pain*
16 159(1):92-105.
- 17 Castellanos A, Pujol-Coma A, Andres-Bilbe A, Negm A, Callejo G, Soto D and others. 2020. TRESK
18 background K. *J Physiol* 598(5):1017-1038.
- 19 Charles AC, Baca SM. 2013. Cortical spreading depression and migraine. *Nat Rev Neurol* 9(11):637-44.
- 20 Coppola G, Petolicchio B, Di Renzo A, Tinelli E, Di Lorenzo C, Parisi V and others. 2017. Cerebral gray
21 matter volume in patients with chronic migraine: correlations with clinical features. *J*
22 *Headache Pain* 18(1):115.
- 23 Coppola G, Vandenheede M, Di Clemente L, Ambrosini A, Fumal A, De Pasqua V and others. 2005.
24 Somatosensory evoked high-frequency oscillations reflecting thalamo-cortical activity are
25 decreased in migraine patients between attacks. *Brain* 128(Pt 1):98-103.
- 26 Czirják G, Enyedi P. 2002. Formation of Functional Heterodimers between the TASK-1 and TASK-3
27 Two-pore Domain Potassium Channel Subunits. *Journal of Biological Chemistry* 277(7):5426-
28 5432.
- 29 De Felice M, Ossipov MH, Wang R, Lai J, Chichorro J, Meng I and others. 2010. Triptan-induced latent
30 sensitization: a possible basis for medication overuse headache. *Ann Neurol* 67(3):325-37.
- 31 De Felice M, Porreca F. 2009. Opiate-induced persistent pronociceptive trigeminal neural
32 adaptations: potential relevance to opiate-induced medication overuse headache.
33 *Cephalalgia* 29(12):1277-84.
- 34 De Fusco M, Marconi R, Silvestri L, Atorino L, Rampoldi L, Morgante L and others. 2003.
35 Haploinsufficiency of ATP1A2 encoding the Na⁺/K⁺ pump alpha2 subunit associated with
36 familial hemiplegic migraine type 2. *Nat Genet* 33(2):192-6.
- 37 Denuelle M, Fabre N, Payoux P, Chollet F, Geraud G. 2007. Hypothalamic activation in spontaneous
38 migraine attacks. *Headache* 47(10):1418-26.
- 39 Descoeur J, Pereira V, Pizzoccaro A, Francois A, Ling B, Maffre V and others. 2011. Oxaliplatin-induced
40 cold hypersensitivity is due to remodelling of ion channel expression in nociceptors. *EMBO*
41 *Mol Med* 3(5):266-78.
- 42 Dichgans M, Freilinger T, Eckstein G, Babini E, Lorenz-Depiereux B, Biskup S and others. 2005.
43 Mutation in the neuronal voltage-gated sodium channel SCN1A in familial hemiplegic
44 migraine. *Lancet* 366(9483):371-7.
- 45 Djillani A, Mazella J, Heurteaux C, Borsootto M. 2019. Role of TREK-1 in Health and Disease, Focus on
46 the Central Nervous System. *Front Pharmacol* 10:379.
- 47 Dobler T, Springauf A, Tovornik S, Weber M, Schmitt A, Sedlmeier R and others. 2007. TRESK two-
48 pore-domain K⁺ channels constitute a significant component of background potassium
49 currents in murine dorsal root ganglion neurones. *J Physiol* 585(Pt 3):867-79.
- 50 Domitrz I, Kosiorek M, Żekanowski C, Kamińska A. 2016. Genetic studies of Polish migraine patients:
51 screening for causative mutations in four migraine-associated genes. *Hum Genomics* 10:3.
- 52 Ducros A. 2013. [Genetics of migraine]. *Rev Neurol (Paris)* 169(5):360-71.

1 Edelmayer RM, Vanderah TW, Majuta L, Zhang ET, Fioravanti B, De Felice M and others. 2009.
2 Medullary pain facilitating neurons mediate allodynia in headache-related pain. *Ann Neurol*
3 65(2):184-93.

4 Edvinsson L, Haanes KA, Warfvinge K, Krause DN. 2018. CGRP as the target of new migraine therapies
5 - successful translation from bench to clinic. *Nat Rev Neurol* 14(6):338-350.

6 Ferrari U, Empl M, Kim KS, Sostak P, Förderreuther S, Straube A. 2005. Calcineurin inhibitor-induced
7 headache: clinical characteristics and possible mechanisms. *Headache* 45(3): 211-214.

8 Frederiksen SD, Haanes KA, Warfvinge K, Edvinsson L. 2019. Perivascular neurotransmitters:
9 Regulation of cerebral blood flow and role in primary headaches. *J Cereb Blood Flow Metab*
10 39(4):610-632.

11 Goadsby PJ, Holland PR, Martins-Oliveira M, Hoffmann J, Schankin C, Akerman S. 2017.
12 Pathophysiology of Migraine: A Disorder of Sensory Processing. *Physiol Rev* 97(2):553-622.

13 Gormley P, Anttila V, Winsvold BS, Palta P, Esko T, Pers TH and others. 2016. Meta-analysis of
14 375,000 individuals identifies 38 susceptibility loci for migraine. *Nat Genet* 48(8):856-66.

15 Gormley P, Kurki MI, Hiekkala ME, Veerapen K, Häppölä P, Mitchell AA and others. 2018. Common
16 Variant Burden Contributes to the Familial Aggregation of Migraine in 1,589 Families. *Neuron*
17 98(4):743-753.e4.

18 Gross EC, Klement RJ, Schoenen J, D'Agostino DP, Fischer D. 2019. Potential Protective Mechanisms
19 of Ketone Bodies in Migraine Prevention. *Nutrients* 11(4).

20 Guo S, Vollesen AL, Olesen J, Ashina M. 2016. Premonitory and nonheadache symptoms induced by
21 CGRP and PACAP38 in patients with migraine. *Pain* 157(12):2773-2781.

22 Guo Z, Liu P, Ren F, Cao YQ. 2014. Nonmigraine-associated TRESK K⁺ channel variant C110R does not
23 increase the excitability of trigeminal ganglion neurons. *J Neurophysiol* 112(3):568-79.

24 Hadjikhani N, Albrecht DS, Mainero C, Ichijo E, Ward N, Granziera C and others. 2020. Extra-axial
25 inflammatory signal in parameninges in migraine with visual aura. *Ann Neurol*.

26 Harriott AM, Gold MS. 2009. Contribution of primary afferent channels to neuropathic pain. *Curr Pain*
27 *Headache Rep* 13(3):197-207.

28 Heurteaux C, Lucas G, Guy N, El Yacoubi M, Thümmeler S, Peng XD and others. 2006. Deletion of the
29 background potassium channel TREK-1 results in a depression-resistant phenotype. *Nat*
30 *Neurosci* 9(9):1134-41.

31 Honoré E. 2007. The neuronal background K^{2P} channels: focus on TREK1. *Nat Rev Neurosci* 8(4):251-
32 61.

33 Hwang EM, Kim E, Yarishkin O, Woo DH, Han KS, Park N and others. 2014. A disulphide-linked
34 heterodimer of TWIK-1 and TREK-1 mediates passive conductance in astrocytes. *Nat*
35 *Commun* 5:3227.

36 Jain A, Liu R, Ramani B, Arauz E, Ishitsuka Y, Rangunathan K and others. 2011. Probing cellular protein
37 complexes using single-molecule pull-down. *Nature* 473(7348):484-8.

38 Kanda H, Ling J, Tonomura S, Noguchi K, Matalon S, Gu JG. 2019. TREK-1 and TRAAK Are Principal K.
39 *Neuron* 104(5):960-971.e7.

40 Karatas H, Erdener SE, GURSOY-OZDEMIR Y, LULE S, EREN-KOÇAK E, SEN ZD and others. 2013. Spreading
41 depression triggers headache by activating neuronal Panx1 channels. *Science*
42 339(6123):1092-5.

43 Karsan N, Goadsby PJ. 2018. Biological insights from the premonitory symptoms of migraine. *Nat Rev*
44 *Neurol* 14(12):699-710.

45 Khan S, Amin FM, Christensen CE, Ghanizada H, Younis S, Olinger ACR and others. 2019. Meningeal
46 contribution to migraine pain: a magnetic resonance angiography study. *Brain* 142(1):93-102.

47 Kochetov AV. 2008. Alternative translation start sites and hidden coding potential of eukaryotic
48 mRNAs. *BioEssays* 30(7):683-691.

49 Kozak M. 1987. An analysis of 5'-noncoding sequences from 699 vertebrate messenger RNAs. *Nucleic*
50 *Acids Research* 15(20):8125-8148.

51 Kozak M. 1999. Initiation of translation in prokaryotes and eukaryotes. *Gene* 234(2):187-208.

- 1 Kunkler PE, Zhang L, Johnson PL, Oxford GS, Hurley JH. 2018. Induction of chronic migraine
2 phenotypes in a rat model after environmental irritant exposure. *Pain* 159(3):540-549.
- 3 Lafrenière RG, Cader MZ, Poulin JF, Andres-Enguix I, Simoneau M, Gupta N and others. 2010. A
4 dominant-negative mutation in the TRESK potassium channel is linked to familial migraine
5 with aura. *Nat Med* 16(10):1157-60.
- 6 Levitz J, Royal P, Comoglio Y, Wdziekonski B, Schaub S, Clemens DM and others. 2016.
7 Heterodimerization within the TREK channel subfamily produces a diverse family of highly
8 regulated potassium channels. *Proceedings of the National Academy of Sciences*
9 113(15):4194.
- 10 Levy D, Labastida-Ramirez A, MaassenVanDenBrink A. 2019. Current understanding of meningeal and
11 cerebral vascular function underlying migraine headache. *Cephalalgia* 39(13):1606-1622.
- 12 Li XY, Toyoda H. 2015. Role of leak potassium channels in pain signaling. *Brain Res Bull* 119(Pt A):73-
13 9.
- 14 Liu P, Xiao Z, Ren F, Guo Z, Chen Z, Zhao H and others. 2013. Functional analysis of a migraine-
15 associated TRESK K⁺ channel mutation. *J Neurosci* 33(31):12810-24.
- 16 Mi Hwang E, Kim E, Yarishkin O, Ho Woo D, Han K-S, Park N and others. 2014. A disulphide-linked
17 heterodimer of TWIK-1 and TREK-1 mediates passive conductance in astrocytes. *Nature*
18 *Communications* 5(1):3227.
- 19 Morenilla-Palao C, Luis E, Fernández-Peña C, Quintero E, Weaver JL, Bayliss DA and others. 2014. Ion
20 channel profile of TRPM8 cold receptors reveals a role of TASK-3 potassium channels in
21 thermosensation. *Cell Rep* 8(5):1571-82.
- 22 Nahman-Averbuch H, Leon E, Hunter BM, Ding L, Hershey AD, Powers SW and others. 2019.
23 Increased pain sensitivity but normal pain modulation in adolescents with migraine. *Pain*
24 160(5):1019-1028.
- 25 Nosedá R, Constandil L, Bourgeois L, Chalus M, Villanueva L. 2010. Changes of meningeal excitability
26 mediated by corticotrigeminal networks: a link for the endogenous modulation of migraine
27 pain. *J Neurosci* 30(43):14420-9.
- 28 Noël J, Zimmermann K, Busserolles J, Deval E, Alloui A, Diochot S and others. 2009. The mechano-
29 activated K⁺ channels TRAAK and TREK-1 control both warm and cold perception. *EMBO J*
30 28(9):1308-18.
- 31 Nyholt DR, Borsook D, Griffiths LR. 2017. Migrainomics - identifying brain and genetic markers of
32 migraine. *Nat Rev Neurol* 13(12):725-741.
- 33 Nyholt DR, LaForge KS, Kallela M, Alakurtti K, Anttila V, Färkkilä M and others. 2008. A high-density
34 association screen of 155 ion transport genes for involvement with common migraine. *Hum*
35 *Mol Genet* 17(21):3318-31.
- 36 Olesen J, Ashina M. 2015. Can nitric oxide induce migraine in normal individuals? *Cephalalgia*
37 35(12):1125-9.
- 38 Olesen J, Burstein R, Ashina M, Tfelt-Hansen P. 2009. Origin of pain in migraine: evidence for
39 peripheral sensitisation. *Lancet Neurol* 8(7):679-90.
- 40 Pereira V, Busserolles J, Christin M, Devilliers M, Poupon L, Legha W and others. 2014. Role of the
41 TREK2 potassium channel in cold and warm thermosensation and in pain perception. *Pain*
42 155(12):2534-44.
- 43 Pettingill P, Weir GA, Wei T, Wu Y, Flower G, Lalic T and others. 2019. A causal role for TRESK loss of
44 function in migraine mechanisms. *Brain* 142(12):3852-3867.
- 45 Plant LD. 2012. A Role for K2P Channels in the Operation of Somatosensory Nociceptors. *Front Mol*
46 *Neurosci* 5:21.
- 47 Plant LD, Zuniga L, Araki D, Marks JD, Goldstein SAN. 2012. SUMOylation Silences Heterodimeric
48 TASK Potassium Channels Containing K2P1 Subunits in Cerebellar Granule Neurons. *Science*
49 *Signaling* 5(251):ra84-ra84.
- 50 Rainero I, Rubino E, Gallone S, Zavarise P, Carli D, Boschi S and others. 2014. KCNK18 (TRESK) genetic
51 variants in Italian patients with migraine. *Headache* 54(9):1515-22.

- 1 Royal P, Andres-Bilbe A, Ávalos Prado P, Verkest C, Wdziekonski B, Schaub S and others. 2019.
2 Migraine-Associated TRESK Mutations Increase Neuronal Excitability through Alternative
3 Translation Initiation and Inhibition of TREK. *Neuron* 101(2):232-245.e6.
- 4 Rua R, McGavern DB. 2018. Advances in Meningeal Immunity. *Trends Mol Med* 24(6):542-559.
- 5 Schulte LH, May A. 2016. Functional Neuroimaging in Migraine: Chances and Challenges. *Headache*
6 56(9):1474-1481.
- 7 Schytz HW, Wienecke T, Olesen J, Ashina M. 2010. Carbachol induces headache, but not migraine-like
8 attacks, in patients with migraine without aura. *Cephalalgia* 30(3):337-45.
- 9 Sheftell F, Rapoport A, Weeks R, Walker B, Gammerman I, Baskin S. 2000. Montelukast in the
10 prophylaxis of migraine: a potential role for leukotriene modifiers. *Headache* 40(2):158-63.
- 11 Spindler BL, Ryan M. 2020. Recent Medications Approved for Preventing Migraine Headaches. *Am J*
12 *Med.*
- 13 Strassman AM, Raymond SA, Burstein R. 1996. Sensitization of meningeal sensory neurons and the
14 origin of headaches. *Nature* 384(6609):560-4.
- 15 Suzuki Y, Tsutsumi K, Miyamoto T, Yamamura H, Imaizumi Y. 2017. Heterodimerization of two pore
16 domain K⁺ channel TASK1 and TALK2 in living heterologous expression systems. *PLOS ONE*
17 12(10):e0186252.
- 18 Thomas D, Plant LD, Wilkens CM, McCrossan ZA, Goldstein SA. 2008. Alternative translation initiation
19 in rat brain yields K2P2.1 potassium channels permeable to sodium. *Neuron* 58(6):859-70.
- 20 Turner DP, Houle TT. 2018. Influences on headache trigger beliefs and perceptions. *Cephalalgia*
21 38(9):1545-1553.
- 22 Uddman R, Edvinsson L, Ekman R, Kingman T, McCulloch J. 1985. Innervation of the feline cerebral
23 vasculature by nerve fibers containing calcitonin gene-related peptide: trigeminal origin and
24 co-existence with substance P. *Neurosci Lett* 62(1):131-6.
- 25 van den Maagdenberg AM, Pietrobon D, Pizzorusso T, Kaja S, Broos LA, Cesetti T and others. 2004. A
26 *Cacna1a* knockin migraine mouse model with increased susceptibility to cortical spreading
27 depression. *Neuron* 41(5):701-10.
- 28 van Dongen RM, Zielman R, Noga M, Dekkers OM, Hankemeier T, van den Maagdenberg AM and
29 others. 2017. Migraine biomarkers in cerebrospinal fluid: A systematic review and meta-
30 analysis. *Cephalalgia* 37(1):49-63.
- 31 Vila-Pueyo M. 2018. Targeted 5-HT. *Neurotherapeutics* 15(2):291-303.
- 32 Vila-Pueyo M, Hoffmann J, Romero-Reyes M, Akerman S. 2019. Brain structure and function related
33 to headache: Brainstem structure and function in headache. *Cephalalgia* 39(13):1635-1660.
- 34 Wright PD, McCoull D, Walsh Y, Large JM, Hadrys BW, Gaurilcikaite E and others. 2019. Pramlukast is
35 a novel small molecule activator of the two-pore domain potassium channel TREK2. *Biochem*
36 *Biophys Res Commun* 520(1):35-40.
- 37 Yamamoto Y, Hatakeyama T, Taniguchi K. 2009. Immunohistochemical colocalization of TREK-1,
38 TREK-2 and TRAAK with TRP channels in the trigeminal ganglion cells. *Neurosci Lett*
39 454(2):129-33.
- 40 Zerimech S, Chever O, Scalmani P, Pizzamiglio L, Duprat F, Mantegazza M. 2020. Cholinergic
41 modulation inhibits cortical spreading depression in mouse neocortex through activation of
42 muscarinic receptors and decreased excitatory/inhibitory drive. *Neuropharmacology*
43 166:107951.

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45