Transcriptional alterations are characteristic of persistent pain states, but the key regulators remain elusive. HDAC4 is a transcriptional corepressor that has been linked to synaptic plasticity and neuronal excitability, mechanisms that may be involved in peripheral and central sensitization. Using a conditional knockout (cKO) strategy in mice, we sought to determine whether the loss of HDAC4 would have implications for sensory neuron transcription and nociception. HDAC4 was found to be largely unnecessary for transcriptional regulation of naïve sensory neurons but was essential for appropriate transcriptional responses after injury, with Calca and Trpv1 expression consistently down-regulated in HDAC4 cKO compared to levels in the littermate controls (0.2–0.44-fold change, n=4 in 2 separate experiments). This down-regulation corresponded to reduced sensitivity to 100 nM capsaicin in vitro (IC50 = 230 ± 20 nM, 76 ± 4.4% wild-type capsaicin responders vs. 56.9 ± 4.7% HDAC4 cKO responders) and to reduced thermal hypersensitivity in the complete Freund’s adjuvant (CFA) model of inflammatory pain (1.3–1.4-fold improvement over wild-type controls; n=5–12, in 2 separate experiments). These data indicate that HDAC4 is a novel inflammatory pain mediator and may be a good therapeutic target, capable of orchestrating the regulation of multiple downstream effectors. —Crow, M., Khovanov, N., Kelleher, J. H., Sharma, S., Grant, A. D., Bogdanov, Y., Wood, J. N., McMahon, S. B., Denk, F. HDAC4 is required for inflammation-associated thermal hypersensitivity. FASEB J. 29, 3370–3378 (2015). www.fasebj.org

Key Words: epigenetics • pain • nerve growth factor • transcription
sodium channel Na\textsubscript{1.8}Cre line, has been extensively used to target small primarily nociceptive neurons of the dorsal root ganglion (DRG) (19). The other line, Advillin-CreERT2, was developed more recently and allows for inducible panneuronal knockout by administration of the estrogen receptor agonist tamoxifen (20).

Our mouse models therefore enabled us to study the absence of HDAC4 in a spatially and temporally selective fashion. Their phenotypes are reported herein. We found that the absence of HDAC4 attenuates the development of chronic inflammatory pain, on both the transcriptional and behavioral levels.

MATERIALS AND METHODS

Animals

All work conformed to United Kingdom Home Office legislation (Scientific Procedures Act 1986) and was performed on animals or tissue taken from 2-mo-old animals, unless otherwise stated in Table 1. All lines were backcrossed for 5 generations to pure C57Bl/6J mice, to achieve near congenicity (>95%) before the experiments. For all the experiments, wild-type and knockout groups were age and sex matched.

Genotyping

The HDAC\textsuperscript{4/0}, Na\textsubscript{1.8}Cre, and Advillin-CreERT2 mouse lines have been described, and genotyping was performed according to established protocols (19–21). Genotyping primers are listed in Table 2.

Tamoxifen dosing

Tamoxifen (T5648; Sigma-Aldrich, Poole, United Kingdom) was prepared according to the protocol of Metzger and Chambon (22). Briefly, 10 mg tamoxifen was dissolved in 100 μl 100% ethanol, made up to 10 mg/ml in autoclaved sunflower oil, and placed on a shaker at room temperature for 2–3 h. The drug was separated into aliquots and stored at −20°C before administration. At 8–20 wk of age, the mice received 2 mg tamoxifen intraperitoneally once daily for 5 d.

Behavior

All behavioral testing was performed on littermate controls by an experimenter blind to genotype on a per animal (rather than per group) basis. On each day, the animals were randomized into test boxes according to the list randomizer function of Random.org (http://www.random.org). Baselines were determined over 3 d. In the case of tamoxifen administration, both knockout animals and their controls received the compound, and testing was performed only after a recovery period of 4 wk.

Von Frey test

The 50% mechanical thresholds were determined with calibrated Von Frey filaments following the up–down method of Dixon (23) and Chaplan et al. (24). The animals were habituated to the testing environment for 60 min before testing. Filaments were applied to the plantar surface of the hind paw for 3 seconds, and a bimodal (yes/no) response was recorded.

Hargreaves test

Heat withdrawal thresholds were assessed with the Hargreaves apparatus (Ugo Basile, Varese, Italy), set to an infrared intensity of 40 and a cutoff time of 32.5 s. The animals were habituated for at least 30 min before testing, and care was taken to ensure that the glass base was kept clean and that the animals were not in deep sleep when measurements were taken, as sleep has been shown to greatly influence withdrawal latencies (25). At least 3 measurements of withdrawal latency were taken per paw on each test day.

Tail-flick test

The tail-flick response was measured at 49 or 52°C to determine spinal reflex responses to innocuous warm and noxious heat stimuli, respectively, according to the protocol of Ben-Bassat et al. (26). Briefly, mice were restrained, the tail immersed in a water bath, and the latency to respond recorded. Three measurements were recorded on the test day, with at least 5 min between trials.

Inflammatory pain model

To model chronic inflammatory pain, a 20 μl intraplantar complete Freund's adjuvant (CFA) (F5881; Sigma-Aldrich) was injected into the right hind paw.

Sciatic nerve crush model of peripheral nerve regeneration

Under isoflurane anesthesia, the sciatic nerve was exposed and crushed with watchmakers forceps coated in lamp black to mark the crush site. The crush site was kept a constant 37 mm from the tip of the third toe, and the wound was closed with wound clips.

Pinprick assay

To assess sensory recovery after sciatic nerve crush, the pinprick test was used (27). Under light restraint, 16 areas of the denervated paw were stimulated with a pin, and responses were scored on a 3-point scale (0, no response; 1, light or inconsistent response; and 2, strong consistent withdrawal response).

DRG dissections

The animals were killed by a fatal overdose of sodium pentobarbitol before transcardial perfusion with PBS. A dorsal laminectomy of the spinal cord was performed in situ. To identify lumbar L3–L5 DRGs, the sciatic nerve was traced up to the spinal cord, and the 3 ganglia attached were dissected, snap frozen in liquid nitrogen, and stored at −80°C before RNA or protein...
on the day of the experiments, cDNA samples were diluted to be ordered from Life Technologies (probes listed in Custom TaqMan low-density RT-quantitative (q)PCR array cards (Foster City, CA). Raw cycle thresholds (CTs) were exported, and qPCR machine (Applied Biosystems-ThermoFisher Scientific, Watham, MA, USA), and 500 ng total RNA was used for subsequent first-strand cDNA synthesis reactions with SuperScript III according to manufacturer’s protocol (Life Technologies, Paisley, United Kingdom).

**TaqMan low-density RT-quantitative PCR array cards**

Custom TaqMan low-density RT-quantitative (q)PCR array cards were ordered from Life Technologies (probes listed in Table 3). On the day of the experiments, cDNA samples were diluted to 2 ng/µl in a final volume of 100 µl PCR mastermix (1×) containing SYBR green in DNAse-free H2O (Qiagen). The samples were mixed by pipetting and loaded into wells, and the cards were spun at 1200 rpm for 2 min, sealed, and run on a 7900HT RT-qPCR machine (Applied Biosystems-ThermoFisher Scientific, Foster City, CA). Raw cycle thresholds (CTs) were exported, and relative quantification was performed in Excel (Microsoft, Redmond, WA, USA) by the ΔΔCT method. Multiple experiment viewer software was used to create data visualization tools.

**RT-qPCR**

RT-qPCR was performed with a LightCycler FastStart DNA MasterPlus SYBR Green I kit (Roche Diagnostics, Burgess Hill, United Kingdom) according to the manufacturer’s protocol on a LightCycler 480 (Roche Diagnostics). All primers had an efficiency of 2.0 ± 0.2. The results were determined from plates where no-template controls were used, to ensure that the reagents were contamination free. Triplicate CTs were averaged, and the results were analyzed by the ΔΔCT method (28).

**Microarray**

RNA was processed by University College London (UCL) Genomics with an Ambion Whole Transcript Expression Kit (Invitrogen-Life Technologies, Carlsbad CA, USA) and hybridized to Mouse Gene 2.0ST Arrays (Affymetrix; Santa Clara, CA, USA) on a GeneChip Fluidics Station 450 (Affymetrix). The chips were read on an Affymetrix GeneChip Scanner. Quality control and analysis were performed with the following bioconductor packages in R: oligo (29) for preprocessing, robust multichip average normalization (30), and various quality controls (including microarray plots, box plots, and principal component analysis) and linear models for microarray data (31) for statistical analysis. Gene Expression Omnibus (GEO) accession: GSE62405 (GEO, National Center for Biotechnology Information, Bethesda, MD, USA).

**Protein extraction and subcellular fractionation**

For Western blot analysis, protein was extracted in 0.2% SDS in double-distilled H2O with 1× protease inhibitor cocktail (Roche Diagnostics). For cell fractionation studies, DRGs were homogenized in 150 µl lysis buffer A for 5 min [0.5% DTT, protease inhibitors, 10 M (4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid; HEPES), 1.5 mM MgCl₂, and 10 mM KCl in H₂O]. The lysates were centrifuged at 1.5 relative centrifugal force (rcf) for 5 min, and the cytoplasmic fraction was removed. The pellets were resuspended in 100 µl of buffer B (buffer A plus 0.5% SDS), sonicated for 2 min, and centrifuged at 5 rcf for 5 min, to obtain nuclear-enriched fractions. Protein concentration was assessed by determining absorbance at 280 nm on a Nanodrop spectrophotometer (ThermoFisher Scientific). Protein lysates were stored at −80°C before reduction for 5 min at 100°C in 1× Laemmli buffer, after which they were stored at −20°C.

**Table 3. TaqMan probe IDs**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cacna2tl-Mm00486607_m1</td>
<td>P2rx3-Mm00523699_m1</td>
<td>Scn3a-Mm00658167_m1</td>
<td>Tacr1-Mm00436892_m1</td>
</tr>
<tr>
<td>Calca-Mm00801462_m1</td>
<td>P2rx4-Mm00501787_m1</td>
<td>Ccss-Mm01255859_m1</td>
<td>Scl0a6-Mm01267368_m1</td>
</tr>
<tr>
<td>Ptg2-Mm00478374_m1</td>
<td>Ngrf-Mm01309635_m1</td>
<td>Vip-Mm00660234_m1</td>
<td>Adcyap1-Mm00437433_m1</td>
</tr>
<tr>
<td>Bdnf-Mm00423060_m1</td>
<td>Sgk1-Mm00441380_m1</td>
<td>Reg3b-Mm00440616_g1</td>
<td>Gad2-Mm00484623_m1</td>
</tr>
<tr>
<td>Hcnc2-Mm00468538_m1</td>
<td>Tac1-Mm01166996_m1</td>
<td>Ccl2-Mm00441242_m1</td>
<td>Gabra3-Mm006621092_m1</td>
</tr>
<tr>
<td>Oprml-Mm00404568_m1</td>
<td>Ntrk1-Mm01219406_m1</td>
<td>Nps-Mm00445771_m1</td>
<td>Gabbr1-Mm00444578_m1</td>
</tr>
<tr>
<td>Scn10a-Mm00501467_m1</td>
<td>Ntrk2-Mm00435422_m1</td>
<td>Gfap-Mm01253033_m1</td>
<td>Gapdh-Mm09999915_g1</td>
</tr>
<tr>
<td>Scn9b-Mm00450762_s1</td>
<td>Ntrk3-Mm00452622_m1</td>
<td>Sst-Mm00436671_m1</td>
<td>Hprt-Mm00446968_m1</td>
</tr>
<tr>
<td>Scn1la-Mm00449377_m1</td>
<td>Trpa1-Mm01227437_m1</td>
<td>Aflf-Mm00479862_g1</td>
<td>Kcnsl-Mm00492824_m1</td>
</tr>
<tr>
<td>Nox1-Mm00435715_m1</td>
<td>Trpv1-Mm00416032_m1</td>
<td>Pdyn-Mm00457573_m1</td>
<td>Gch1-Mm01322973_m1</td>
</tr>
<tr>
<td>18S-Hm99999901_s1</td>
<td>Tph-Mm00476032_m1</td>
<td>Egfr-Mm00433023_m1</td>
<td>Nglf-Mm00443039_m1</td>
</tr>
<tr>
<td>Rest-Mm00803268_m1</td>
<td>Gal-Mm00439056_m1</td>
<td>Ccr2-Mm00438270_m1</td>
<td>Vgf-Mm01204485_s1</td>
</tr>
</tbody>
</table>

**electrophoresis of the PCR products (Table 4). All primers had an efficiency of 2.0 ± 0.2. The results were determined from plates where no-template controls were used, to ensure that the reagents were contamination free. Triplicate CTs were averaged, and the results were analyzed by the ΔΔCT method (28).**
Western blot analysis

Protein (20 μg) was run on NuPAGE Novex 10% Bis-Tris Gels (Invitrogen-Life Technologies) and transferred onto 0.45-μm PVDF membranes (Millipore, Stonehouse, United Kingdom). The membranes were blocked in milk and incubated overnight at 4°C with HDAC4 (1:500, sc-11418; Santa Cruz Biotechnology, Dallas, TX, USA), HDAC5 (1:1000, H4538; Sigma-Aldrich.), HDAC9 (1:500, ab18970; Abcam, Cambridge, United Kingdom), α-tubulin (Sigma-Aldrich) or H3 (1:10,000, ab1791; Abcam). After they were washed, the membranes were incubated in secondary antibody for 1 h (1:5000, horseradish peroxidase conjugated anti-rabbit or anti-mouse; GE Healthcare, Little Chalfont, United Kingdom). The signal was detected using an enhanced chemiluminescence prime kit (GE Healthcare) and visualized with a UVP GelDoc-It Imaging system (Ultra-Violet Technologies, Ann Arbor, MI, USA). Briefer, snap-frozen lumbar DRGs were homogenized in 290 μl enzyme immunoassay buffer and run in duplicate wells, according to the manufacturer’s instructions.

Dissociated DRG culture

After cervical dislocation and dorsal laminectomy, the DRGs were dissected into F12 media (Life Technologies-Gibco, Grand Island, NY, USA). Ganglia were digested for 1 h at 37°C in a final concentration of 0.125% collagenase (Sigma-Aldrich) and 0.1 mg/ml DNase I (Sigma-Aldrich), washed in 3 ml warm F12, and triturated in 2 ml F12 supplemented with 0.3% BSA (Sigma-Aldrich), 1× N2 supplement (Life Technologies-Gibco), and 1× penicillin/streptomycin (Sigma-Aldrich). The cell pellet was resuspended in supplemented F12 with 50 mg/ml mouse nerve growth factor (NEB, R&D Systems, Minneapolis, MN, USA) and plated onto coverslips precoated with poly-L-lysine (Invitrogen-Life Technologies) and 0.01 mg/ml laminin (Sigma-Aldrich).

Immunocytochemistry

Cultured primary sensory neurons were washed 3 times with warm PBS and fixed with 4% paraformaldehyde (PFA) for 20 min at room temperature. They were then washed in PBS, blocked in 10% normal goat or donkey serum in PBS + 0.2% Triton X+0.1% sodium azide for 30 min and incubated with 1:1000 anti-mouse β-III-tubulin (Promega, Madison, WI, USA) for 1 h, washed and incubated in 1:1000 Alexa-Fluor 488 (Invitrogen-Life Technologies) and 1:10,000 DAPI (Life Technologies) for a further 1 h.

Calcium imaging

DRG neurons were used for Ca2+ imaging experiments after 18–24 h in culture. Cells were incubated in buffer [HBSS with 10 mM glucose and 10 mM HEPES (pH 7.4)] with Fura 2-acetoxymethyl ester (2 μM) and probenecid (1 mM) for 60 minutes at 37°C, and the coverslips were washed and mounted for imaging. Capsaicin was made up to 100 nM in buffer and applied to cells by continuous perfusion. Individual cell fluorescence was measured at 340 and 380 nm excitation and 510 nm emission with a microscope-based imaging system (PTI, Ford, United Kingdom). At the end of each experiment, the cells were challenged with KCl (50 mM) to provide a maximum Ca2+ signal against which to normalize responses. Neurons were identified morphologically and were excluded from analysis if they did not respond to KCl.

Immunohistochemistry

Adult animals were transcardially perfused with freshly prepared 4% PFA in 0.1 M phosphate buffer (PB; pH 7.4-7.7) before dissection. Tissue was postfixed at 4°C for 3 h in 4% PFA in 0.1 M PB, followed by 24 h at 4°C in 20% sucrose solution in 0.1 M PB. Skin samples were blocked in optimal cutting temperature compound (Tissue-Tek; Sakura Finetek, Torrance CA, USA), frozen in liquid nitrogen, and stored at −80°C. Frozen sections were cut at 12 μm on a cryostat. The slides were dried for at least 1 h and stored at −20°C until further processing. The slides were then blocked for 30–60 min in 10% normal goat or donkey serum, incubated overnight at room temperature with anti-rabbit PGP9.5 (1:1000; Ultraclone, Isle of Wight, United Kingdom), incubated for 2 h in anti-rabbit Alexa 488 (1:1000; Invitrogen-Life Technologies), and mounted with Vectashield (Vector Laboratories, Peterborough, United Kingdom).

Microscopy and image analysis

For each experiment, a minimum of 3 sections from 3 animals per group were used for analysis. To avoid bias, images were taken and processed in a blinded manner: the animals were assigned randomized numbers at the time of dissection that were not revealed until the analysis was completed. Images were taken with a Zeiss Axioplan 2 fluorescence microscope (Zeiss, Jena, Germany). Counting and cell size measurements were performed with Image J (National Institutes of Health, Bethesda, MD, USA) and Axiovision software (Zeiss), respectively.

Statistical analysis

Statistical analysis was performed with SPSS, version 21 (IBM, Armonk, NY, USA). Single behavioral measures, immunohistochemical

---

**TABLE 4. RT-qPCR primers**

<table>
<thead>
<tr>
<th>Target gene</th>
<th>Forward (5‘-3‘)</th>
<th>Reverse (5‘-3‘)</th>
</tr>
</thead>
<tbody>
<tr>
<td>β-2-Microglobulin</td>
<td>GCTGTATGGCATCCGAAACCC</td>
<td>TGTGAGCCCGGTTGGACCTGT</td>
</tr>
<tr>
<td>Hdac4 exon 1–2</td>
<td>TGAAGCTTTGACCTGAGGCC</td>
<td>AGGAATCCAGGCGACTCTAG</td>
</tr>
<tr>
<td>Hdac4 exon 6–7</td>
<td>CGACGTCATCCGTCATTGG</td>
<td>AGGCTGTACACCCACCTCTGG</td>
</tr>
<tr>
<td>Hdac5</td>
<td>TGCTACGGCGAGATTGTG</td>
<td>TGGAGAAGCCGGAGACCAAG</td>
</tr>
<tr>
<td>Hdac9</td>
<td>GGGAGAGCAAGATGCTGACAG</td>
<td>TGGGTTTTCCCTCCAGTGG</td>
</tr>
<tr>
<td>Nfk1</td>
<td>ATATCATGGCGCTGACCTTGGT</td>
<td>GTCATGCGCAAACTTCG</td>
</tr>
<tr>
<td>Typ1</td>
<td>AAGCAGGGCAAGATGCTGACAG</td>
<td>CATCATCAACAGGAGACCAAG</td>
</tr>
<tr>
<td>Yehaz</td>
<td>AGTCGTACAAAGACAGCAGCTAA</td>
<td>AGGCAGAACAAGGTCTGGAAG</td>
</tr>
</tbody>
</table>

---

3733

counts, and RT-qPCR data were analyzed using 2-sample Student’s t test, assuming unequal variances. Tests with repeated measures were analyzed with repeated-measures ANOVA. Data are presented as means ± SEM.

RESULTS

To determine whether HDAC4 is involved in sensory neuron function, we took advantage of 2 strains of HDAC4 cKOs, hereafter referred to as HDAC4Nav1.8 and HDAC4Adv.

RT-qPCR and Western blot analysis were used to confirm reduction of HDAC4 expression in HDAC4fl/fl Cre-positive animals (Fig. 1A–D). Because of the cell-type specificity of the Cre lines, residual expression of HDAC4 is expected and is likely to arise from nontargeted cells. To determine whether other class II HDACs are up-regulated in the absence of HDAC4, we used RT-qPCR to compare mRNA between cKOs and wild-type littermate controls. Although the expression of Hdac5 and Hdac9 mRNA in HDAC4 cKOs, hereafter referred to as HDAC4Nav1.8 cKOs. (Supplemental Fig. 1). Because of the cell-type specificity of the Cre lines, residual expression of HDAC4 is unaffected, there was significant up-regulation of Hdac9 mRNA in both strains of HDAC4 cKOs (Fig. 1E, F), which may help to buffer the deleterious effects of HDAC4 knockout in these mice. That this could be a possibility was underscored by subcellular localization data, which indicated that HDAC9 expression is restricted to the nucleus in wild-type DRGs. Meanwhile, HDAC4 and HDAC5 were found in both cytoplasmic and nuclear compartments (Supplemental Fig. 1).

Having established successful knockout of HDAC4, we moved on to investigate its role in normal sensory function. Previous work on HDAC4 has implicated it in regulating the expression of the Runt-related family of transcription factors, which are critical for sensory neuron differentiation (33). For example, forced Runx1 overexpression in response to the Tau promoter leads to a marked reduction of Thra-positive cells (34). Because Nav1.8-Cre is expressed during embryonic development, we hypothesized that loss of HDAC4 at this time could phenocopy runx1-overexpressing mutants. However, no overt morphologic changes were observed in the DRGs of HDAC4Nav1.8 cKOs. (Supplemental Fig. 2).

In addition, previous work has indicated that HDAC4 is necessary for acute sensation of noxious heat, as mice with global knockout of the putative catalytic domain of HDAC4 are insensitive to the hot plate test (16). In our model, however, sensory-neuron-specific knockout of HDAC4 did not alter baseline mechano- or thermosensation, nor did it affect responses to noxious heating of the tail or hind paws (Fig. 2). Furthermore, our microarray analysis of lumbar DRGs from naïve adult HDAC4Nav1.8 cKOs and wild-type littermates indicated that HDAC4 is not necessary for baseline mRNA expression maintenance in sensory neurons, as no genes were found to be significantly

---

**Figure 1.** Nav1.8- and Advillin-Cre expression successfully causes deletion of Hdac4fl/fl in the DRGs. A, B) Hdac4 mRNA levels were measured by RT-qPCR with exon-spanning primers. Both exon 1 and 2 and the floxed exons 6 and 7 were significantly less expressed in HDAC4 cKOs (n = 3–4). *P < 0.05; Student’s t test. C, D) Western blots confirm knockdown of HDAC4 protein in the DRGs. E, F) The mRNA levels of 2 other class IIa HDACs, Hdad5 and Hdad9 were tested (Hdad7 is not expressed in the DRGs [32]). Hdad9 was significantly up-regulated in both strains of HDAC4 cKOs (n = 4). wt, wild-type. *P < 0.05; Student’s t test.
differentially expressed between groups, at a false-
discovery rate threshold of $q < 0.05$ (Supplemental Fig. 3). This finding is consistent with that in a previous report on the HDAC4CamKIIacKO line (15); however, it cannot be separated from the putative compensation by increased levels of HDAC9 mRNA.

In summary, our data do not support an important role for HDAC4 in sensory neuron development or normal sensory neuron function. Next, we examined whether it might play a role after injury. Peripheral sensory neurons have the unique capacity to regenerate, and there is strong evidence for the involvement of another class II HDAC, HDAC5, in this process (35, 36). Here, we used the sciatic crush model of nerve injury, which is reversible and causes acute sensorimotor disturbances and denervation of skin afferents (37). Comparison of wild-type and HDAC4Adv cKOs after sciatic crush injury revealed that peripheral expression of HDAC4 is unnecessary for functional recovery, as assessed by the pinprick test and the regrowth of intraepidermal nerve fibers into the hind paw (Fig. 3). Consistent with the lack of phenotype in vivo, we did not observe any differences in axonal outgrowth between HDAC4Nav1.8 cKOs and littermate cultures in an in vitro model (Fig. 4).

In contrast, we found evidence that HDAC4 may be involved in sensory neuron sensitization. We studied 2 mediators of acute sensitization in vitro: NGF and capsaicin. NGF-treated cKO cultures showed differential transcript expression compared to that in the wild-type controls, as measured by custom-designed TaqMan low-density RT-qPCR array cards (Life Technologies). Several genes were affected (Table 5), including the high-affinity NGF receptor-1, Ntrk1; the gene encoding CGRP, Calca; the transient receptor potential vanilloid 1 ion channel, TRPV1; and other genes involved in pain processing and modulation. These results suggest that HDAC4 may play a role in the modulation of acute nociception, possibly through its regulation of NGF signaling.

Figure 3. HDAC4 is not necessary for neuronal regeneration in vivo. A) Six months after sciatic nerve crush, hind paw skin sections were stained with PGP9.5 to mark nerve fibers (green) and DAPI to visualize the epidermal border and assess skin reinnervation. Crossing fibers are indicated by arrows. Scale bar, 50 µm. B) Sensory recovery after sciatic nerve crush was measured by the pinprick test. No difference was observed between genotypes.
and the NGF-inducible peptide, Vgf. An independent RT-qPCR for Ntrk1 confirmed down-regulation of this target (Supplemental Fig. 4A). As in the naïve condition, a trend toward up-regulation of Hdac9 was also observed (Supplemental Fig. 4B).

TRPV1 is a capsaicin-sensitive cation channel; therefore, its activity in the presence of capsaicin can be monitored using calcium imaging. In concordance with lower levels of Trpv1 mRNA, significantly fewer HDAC4cKO cKO neurons than wild-type neurons responded to capsaicin treatment in vitro (Fig. 5). The maximum capsaicin response remained unchanged, suggesting that the reduction in Trpv1 mRNA expression was more likely to have been caused by the loss of expression in a subset of cells rather than by the reduced expression of Trpv1 in all capsaicin-sensitive cells.

**TABLE 5. TaqMan array results, arranged by probability**

<table>
<thead>
<tr>
<th>Gene</th>
<th>P value</th>
<th>Fold change (cKO/wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ntrk1</td>
<td>0.00</td>
<td>0.37</td>
</tr>
<tr>
<td>P2rx3</td>
<td>0.01</td>
<td>0.41</td>
</tr>
<tr>
<td>Gch1</td>
<td>0.01</td>
<td>0.37</td>
</tr>
<tr>
<td>Trpv1</td>
<td>0.01</td>
<td>0.41</td>
</tr>
<tr>
<td>Ngf</td>
<td>0.01</td>
<td>2.04</td>
</tr>
<tr>
<td>Calca</td>
<td>0.02</td>
<td>0.35</td>
</tr>
<tr>
<td>Kns1</td>
<td>0.02</td>
<td>0.36</td>
</tr>
<tr>
<td>Scn9a</td>
<td>0.02</td>
<td>1.78</td>
</tr>
<tr>
<td>Atf3</td>
<td>0.02</td>
<td>0.72</td>
</tr>
<tr>
<td>Sst</td>
<td>0.02</td>
<td>8.04</td>
</tr>
<tr>
<td>Reg3b</td>
<td>0.03</td>
<td>31.11</td>
</tr>
<tr>
<td>Vip</td>
<td>0.03</td>
<td>17.24</td>
</tr>
<tr>
<td>Gad2</td>
<td>0.05</td>
<td>4.76</td>
</tr>
<tr>
<td>Vgf</td>
<td>0.05</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**DISCUSSION**

HDAC4 and other class II HDACs have been shown to be involved in several processes that may influence sensory neuron development, pain, and regeneration. We sought to determine the role of peripheral expression of HDAC4 by using a cKO approach in mice.

Our results indicated a clear role for HDAC4 in peripheral sensitization and inflammatory hypersensitivity. In separate strains of HDAC4 cKOs, there was significant transcriptional dysregulation of genes that are involved in pain sensitivity, such as Calca and Trpv1. Moreover, CIA-induced inflammatory hypersensitivity was attenuated by sensory-neuron–specific HDAC4 knockout.

The precise mechanisms of this process are still unclear. Increased expression of Calca and Trpv1 has been linked to thermal hypersensitivity (36, 37). Down-regulation of these 2 transcripts, as observed in our knockout animals, could therefore be expected to result in the reduced inflammatory responses evinced by our knockout mice. Since HDAC4 negatively regulates transcription, it is unlikely to modulate these targets directly, as deletion would be predicted to result in increased expression. Moreover, a published HDAC4 chromatin immunoprecipitation study in neurons also does not support HDAC4 binding to these genes (40). Instead, the direction of change may imply that HDAC4 is necessary in suppressing another negative transcription factor that in turn reduces Trpv1 and Calca levels. However, a cytoplasmic mechanism cannot be ruled out. It is possible that cytoplasmic HDAC4 promotes sumoylation or deacetylation of TRPV1 or other mediators that regulate its expression. In this case, the loss of HDAC4 could alter the activity of these proteins.

In contrast to peripheral sensitization, there was no evidence of a role of HDAC4 in naïve DRGs. Sensory neuron development, thermo- and mechanosensation, and adult transcriptional profiles were all unaffected by the lack of HDAC4. Neuronal regeneration was also observed to be
intact. As noted in the Results, up-regulation of HDAC9 was observed in both knockout mouse strains. Whether HDAC9 provided functional compensation for HDAC4 was not directly addressed in the study—an important caveat for the interpretation of the negative results.

In conclusion, HDAC4 is essential for the full establishment of inflammatory hypersensitivity in mice. The evidence showed that HDAC4 can regulate a variety of important pain mediators, including members of the NGF signaling pathway. Interference with this single upstream regulator could therefore have wide-ranging consequences for pain perception. Further study of HDAC4 and similar epigenetic mediators may open up novel therapeutic avenues.

**Figure 5.** HDAC4 gene transcription and capsaicin sensitivity in vitro. A) Representative fluorescence traces from calcium imaging experiments. C = 100 nM capsaicin; K = 50 mM KCl. HDAC4fl/fl left, HDAC4Nav1.8 cKO right. B) Mean peak capsaicin response was plotted as a percentage of the maximum response to KCl. C) Cells were considered capsaicin responsive if the capsaicin peak was >20% of the KCl peak. Significantly fewer HDAC4Nav1.8 cKO neurons responded to capsaicin treatment (n = 5–6). ***P < 0.001; Fisher’s exact test.

**Figure 6.** HDAC4 is essential for inflammation-associated transcriptional regulation and thermal hypersensitivity. A) Heat map of mean-centered gene expression changes in ipsilateral (ipsi) L3–L5 DRGs at d 15 after CFA. In the absence of HDAC4, many genes were under-expressed compared to their levels in the wild-type controls, including Calca, the gene encoding CGRP (n = 4). wt, wild-type. P < 0.01; Student’s t test. B) CGRP protein levels were measured by ELISA in ipsi L3–L5 DRGs at d 7 after CFA. The HDAC4Adv cKOs had significantly lower levels of CGRP than did the wild-type controls (n = 4/group). **P = 0.006; Student’s t test. C) Thermal hyperalgesia was measured with the Hargreaves test. Significant attenuation of thermal hypersensitivity was observed in both strains of HDAC4 cKOs compared to that in the wild-type littermate controls: HDAC4 Nav1.8 (n = 5); HDAC4Adv (n = 6–12). Repeated-measures ANOVA.
REFERENCES


Received for publication December 3, 2014. Accepted for publication April 16, 2015.