

Roles of glutamate, substance P, and gastrin-releasing peptide as spinal neurotransmitters of histaminergic and nonhistaminergic itch



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ABSTRACT

We investigated roles for substance P (SP), gastrin-releasing peptide (GRP), and glutamate in the spinal neurotransmission of histamine-dependent and -independent itch. In anesthetized mice, responses of single superficial dorsal horn neurons to intradermal (i.d.) injection of chloroquine were partially reduced by spinal application of the α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate antagonist 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX). Co-application of CNQX plus a neurokinin-1 (NK-1) antagonist produced stronger inhibition, while co-application of CNQX, NK-1, and GRP receptor (GRPR) antagonists completely inhibited firing. Nociceptive-specific and wide dynamic range-type neurons exhibited differential suppression by CNQX plus either the GRPR or NK-1 antagonist, respectively. Neuronal responses elicited by i.d. histamine were abolished by CNQX alone. In behavioral studies, individual intrathecal administration of a GRPR, NK-1, or AMPA antagonist each significantly attenuated chloroquine-evoked scratching behavior. Co-administration of the NK-1 and AMPA antagonists was more effective, and administration of all 3 antagonists abolished scratching. Intrathecal CNQX alone prevented histamine-evoked scratching behavior. We additionally employed a double-label strategy to investigate molecular markers of pruritogen-sensitive dorsal root ganglion (DRG) cells. DRG cells responsive to histamine and/or chloroquine, identified by calcium imaging, were then processed for co-expression of SP, GRP, or vesicular glutamate transporter type 2 (VGLUT2) immunofluorescence. Subpopulations of chloroquine- and/or histamine-sensitive DRG cells were immunopositive for SP and/or GRP, with >80% immunopositive for VGLUT2. These results indicate that SP, GRP, and glutamate each partially contribute to histamine-independent itch. Histamine-evoked itch is mediated primarily by glutamate, with GRP playing a lesser role. Co-application of NK-1, GRP, and AMPA receptor antagonists may prove beneficial in treating chronic itch.

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1. Introduction

Chronic itch is a burdensome clinical problem that decreases the quality of life [55], yet the neural mechanisms of itch are still not fully understood. Recent studies have implicated histamine-dependent and histamine-independent pathways in transmitting itch. The histamine-independent itch pathway involves members of the family of over 50 Mas-related G-protein-coupled receptors (Mrgprs), in particular, MrgprAs, MrgprB4-5, MrgprC11, and MrgprD, which are restricted to small-diameter dorsal root ganglion (DRG) neurons in mice [21]. Chloroquine and the bovine adrenal medulla peptide 8–22 elicited itch-related scratching

through MrgprA3 and MrgprC11, respectively, in mice [32], and both compounds elicit itch in humans [1,46]. β -Alanine elicited itch via MrgprD [31]. It was recently reported that MrgprA3-expressing primary sensory neurons play a predominant role in itch evoked by chloroquine and other pruritogens [27], implying that spinal neurons with input from such chloroquine-sensitive primary afferents selectively signal itch sensation.

Neurokinin-1 (NK-1) and gastrin-releasing peptide (GRP) receptor (GRPR)-expressing spinal neurons are implicated in signaling itch [11,50]. Their respective ligands, substance P (SP) and GRP, are partially involved in the spinal transmission of itch signals [9,49]. The predominant excitatory neurotransmitter, glutamate, may additionally contribute to itch. A recent electrophysiological study suggested that glutamate acts as a neurotransmitter at GRP-sensitive spinal neurons [29]. In contrast, the genetic ablation of the vesicular glutamate transporter type 2 (VGLUT2), which is essential for glutamate release from the majority of A- and C-fiber

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nociceptors [42], resulted in reduced nocifensive behavior and enhanced spontaneous and pruritogen-evoked scratching [30,36]. A very recent study reported that natriuretic polypeptide B (Nppb) is the primary transmitter released by pruritogen-sensitive primary afferents in mice [36]. Nppb excites GRPR-expressing spinal interneurons that are essential in transmitting itch, but not pain, signals to higher centers [36,46,47].

In the present study we used a multidisciplinary approach to investigate the roles of SP, GRP, and glutamate in the spinal transmission of itch. In electrophysiological experiments, we tested if chloroquine-evoked responses of superficial dorsal horn neurons are inhibited by spinal application of antagonists of NK-1, GRP, and/or glutamate α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptors. Complementary behavioral experiments investigated if these receptor antagonists alone or in combination attenuated chloroquine- and histamine-evoked scratching. Using a combination of calcium imaging followed by immunohistochemistry, we investigated the expression of SP, GRP, and VGLUT2 in pruritogen-sensitive primary sensory neurons.

2. Materials and methods

2.1. Electrophysiology

Experiments were performed using 118 adult male C57BL/6 mice (18–33 g) under a protocol approved by the University of California Davis Animal Care and Use Committee. The single-unit recording from the lumbar spinal cord was conducted as previously detailed [3,7]. Anesthesia was induced by sodium pentobarbital (60 mg/kg intraperitoneal) and maintained by supplemental injections (10–20 mg/kg/h). A gravity-driven perfusion system allowed artificial cerebrospinal fluid (Krebs: 117 mM NaCl, 3.6 mM KCl, 2.5 mM CaCl₂, 1.2 mM MgCl₂, 1.2 mM NaH₂PO₄, 25 mM NaHCO₃, and 11 mM glucose, which was equilibrated with 95% O₂ and 5% CO₂ at 37 °C) to be superfused continually over the exposed lumbosacral spinal cord [6]. A tungsten microelectrode recorded single-unit activity in the lumbar spinal cord. A chemical search strategy [3,7] was used to identify and isolate chloroquine-responsive units. Our search strategy was intended to maximize the chance of isolating a chloroquine-responsive neuron; we assume that such neurons either gave rise to ascending projections, or served as interneurons in segmental scratch-reflex circuitry, and no attempt was made to distinguish between these possibilities. Briefly, a small (~0.25 μ L) intradermal (i.d.) microinjection of chloroquine (100 μ g/ μ L) was made in the ventral hind paw and a spontaneously active unit in the superficial lumbar dorsal horn (depth <300 μ m) was isolated. After the spontaneous activity had waned, chloroquine (1 μ L, 100 μ g/ μ L) was injected again at the same site through the same needle. Only units exhibiting an increase of >30% in firing to this second test microinjection of chloroquine were selected for further study. Responses were usually recorded for at least 30 minutes, although in many cases, unit firing declined over a shorter period.

During the time that the unit exhibited a relatively stable level of chloroquine-evoked firing (usually 1 minute postinjection), one of the following antagonists was successively delivered directly at the spinal cord for 1 minute: the GRP receptor antagonist RC-3095 (20 μ M), the NK-1 receptor antagonist L-733060 (200 μ M), the AMPA/kainate receptor antagonist 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX; 100 μ M), a combination of CNQX (100 μ M) and L-733060 (200 μ M), or a combination of RC-3095 (20 μ M), CNQX (100 μ M), and L-733060 (200 μ M).

When unit firing to the second chloroquine injection declined and reached a steady level, the unit's mechanosensitive receptive field was determined. The perimeter of the mechanical receptive

field was mapped using a von Frey filament (55 mN bending force) by determining sites at which the unit either did (within receptive field) or did not (outside receptive field) respond to at least 3 of 5 repeated applications. The rationale for choosing this bending force is that it was sufficient to map the maximum extent of the mechanical receptive field as assessed by comparison of receptive field sizes mapped using a range of von Frey stimuli (0.7 mN: 1.2 ± 0.6 mm², 6.9 mN: 3.7 ± 0.9 mm², 55 mN: 9.9 ± 1.4 mm², 758 mN: 10.3 ± 1.4 mm²). Units were classified as wide dynamic range (WDR)-type if they responded in a graded manner to innocuous mechanical stimulation (brushing, cotton wisp) and noxious pinch, or nociceptive-specific (NS) if they responded to noxious pinch (and to the 55 mN von Frey stimulus) but not to the cotton wisp or brush stimuli. The properties are similar to those of WDR and NS units shown in previous studies to respond to histamine, serotonin, the protease-activated receptor-2 (PAR-2)/MrgprC11 agonist SLIGRL, or chloroquine [3,7]. In some units, at least 5 minutes after the noxious pinch stimulus, either the NK-1 receptor antagonist or the AMPA/kainate receptor antagonist, or a mixture of both was superfused directly over the spinal cord for 1 minute. At the end of the antagonist superfusion, the noxious pinch stimulus was delivered again at the same site on the receptive field. Thirty minutes later, the noxious pinch stimulus was delivered in the same manner.

Following mechanical stimulation, histamine (50 μ g) was injected i.d. within the same receptive field at a different location via a separate injection cannula. Following the i.d. histamine injection, we tested the effects of antagonists for the receptors of NK1, GRP, or AMPA/kainate in the same manner as described above for chloroquine. Units were then tested with topical hind paw application of allyl isothiocyanate (AITC; mustard oil, 75% in mineral oil, 2 μ L; Sigma–Aldrich, St. Louis, MO, USA). Following the AITC application, we tested the effects of the NK-1 receptor antagonist, the AMPA/kainate receptor antagonist, or a combination of both antagonists in the same manner as described above for chloroquine.

Action potentials were recorded to a computer and counted using Chart software (AD Instruments, Colorado Springs, CO, USA) and Spike2 software (CED Instruments, Cambridge, UK). Ongoing responses elicited by chloroquine, histamine, or AITC were averaged at 20-second intervals before, during, and after the antagonist application, and compared by one-way repeated-measures analysis of variance (ANOVA) followed by post hoc Bonferroni test, with $P < 0.05$ set as significant. The mean firing rate was calculated over a 20-second period 40 seconds after the antagonist application and compared by one-way ANOVA followed by post hoc Bonferroni test, with $P < 0.05$ set as significant. The criterion for decrease in ongoing firing was >70% decrease below the ongoing activity elicited by pruritogen over a 20-second period 40 seconds after the antagonist application. Mean peak responses elicited by noxious pinch were compared by one-way repeated-measures ANOVA followed by post hoc Bonferroni test, with $P < 0.05$ set as significant. At the end of each experiment, an electrolytic lesion was made at the spinal cord recording site. The spinal cord was postfixed in 10% buffered formalin, cut into 50- μ m frozen sections, and examined under the light microscope to identify lesions.

2.2. Behavior

Experiments were conducted using adult male C57BL/6 mice (19–25 g; Simonsen, Gilroy, CA, USA) under a protocol approved by the UC Davis Animal Care and Use Committee. The fur on the rostral back was shaved and mice were habituated to the Plexiglas recording arena 1 week prior to testing. For intrathecal injections, either vehicle (saline), the GRP receptor antagonist RC-3095 (0.3 nmol; Sigma–Aldrich), the NK-1 antagonist L-733060

(22.7 nmol; Tocris Bioscience, Minneapolis, MN, USA), the AMPA/kainate antagonist CNQX (20 nmol; Tocris Bioscience), a combination of CNQX (20 nmol) and L-733060 (22.7 nmol), or a combination of RC-3095 (0.3 nmol), CNQX (20 nmol), and L-733060 (22.7 nmol) was administered by lumbar puncture, followed 5 minutes later by i.d. injection (10 μ L) of either chloroquine (193 nmol; Sigma–Aldrich) or histamine (271 nmol; Sigma–Aldrich). Microinjections were made i.d. in the nape of the neck using a 30-G needle attached to a Hamilton microsyringe by PE-50 tubing. Immediately after the i.d. injection, the mouse was placed into the arena and videotaped from above for 30 minutes. Generally, 3–4 mice were injected and videotaped simultaneously. Immediately after commencing videotaping, all investigators left the room.

Videotapes were reviewed by investigators blinded to the treatment, and the number of scratch bouts was counted at 5-minute intervals. A scratch bout was defined as one or more rapid back-and-forth hind paw motions directed toward and contacting the injection site, and ending with licking or biting of the toes and/or placement of the hind paw on the floor. Hind paw movements directed away from the injection site (eg, ear-scratching) and grooming movements were not counted. One-way ANOVA followed by the Bonferroni posttest was used to compare the total number of scratch bouts across pretreatment groups. In all cases, $P < 0.05$ was considered to be significant. Data for effects of individual antagonist of either NK-1 or GRP receptor on scratching evoked by either histamine or chloroquine were modified from our recent study [9].

2.3. Calcium imaging

A total of 20 adult male C57BL/6 mice (7–9 weeks old, 18–21 g; Simonsen) were used under a protocol approved by the UC Davis Institutional Animal Care and Use Committee. The animal was euthanized under sodium pentobarbital anesthesia and lumbar DRGs were acutely dissected and enzymatically digested at 37 °C for 10 minutes in Hanks' balanced salt solution (HBSS; Invitrogen, Carlsbad, CA, USA) containing 20 units/mL papain (Worthington Biochemical, Lakewood, NJ, USA) and 6.7 mg/mL L-cysteine (Sigma), followed by 10 minutes at 37 °C in HBSS containing 3 mg/mL collagenase (Worthington Biochemical). The ganglia were then mechanically triturated using fire-polished glass pipettes. DRG cells were pelleted, suspended in Minimum Essential Medium Eagle's with Earle's BSS (Gibco, Life Technologies, Grand Island, NY, USA) containing 100 U/mL penicillin, 100 μ g/mL streptomycin (Gibco), 1 \times vitamin (Gibco), and 10% horse serum (Quad Five, Rye-gate, MT, USA), plated on poly-D-lysine-coated glass coverslips, and cultured for 16–24 hours.

DRG cells were incubated in Ringers solution (pH7.4; 140 mM NaCl, 4 mM KCl, 2 mM CaCl₂, 1 mM MgCl₂, 10 mM HEPES and 4.54 mM NaOH) with 10 μ M of Fura-2 AM and 0.05% of Pluronic F-127 (Invitrogen). Coverslips were mounted on a custom-made aluminum perfusion block and viewed through an inverted microscope (Nikon TS100, Technical Instruments, San Francisco, CA, USA). Fluorescence was excited by UV light at 340 nm and 380 nm, alternately, and emitted light was collected via a CoolSnap camera attached to a Lambda LS lamp and a Lambda optical filter changer (Sutter Instrument Company, Novato, CA, USA). Ratiometric measurements were made using Simple PCI software (Compix Inc, Cranberry Township, PA, USA) every 3 seconds.

Solutions were delivered by a solenoid-controlled 8-channel perfusion system (ValveLink, AutoM8; Automate Scientific, Berkeley, CA, USA). Chloroquine (300 μ M) or histamine (100 μ M) was delivered, followed by potassium at a concentration of 144 mM. Stimulus duration was 30 seconds. Ratios were normalized to baseline. Cells were judged to be sensitive if the ratio value

increased by more than 10% of the resting level following chemical application. Only cells responsive to high-K⁺ were included for analysis. After the experiment, coverslips were marked with a diamond pen to provide landmarks for alignment with subsequent immunohistochemistry labeling of the same cells.

2.4. Immunocytochemistry

After calcium imaging, DRG cells in the culture dish were fixed in 4% paraformaldehyde followed by 30% sucrose and then incubated with 5% normal serum. They were immunostained with anti-rabbit GRP antibody (1:500; ImmunoStar Inc, Hudson, WI, USA), anti-rat SP antibody (1:500; Millipore, Billerica, MA, USA), and anti-guinea pig VGLUT2 antibody (1:300; Frontier Institute Co Ltd, Ishikari, Hokkaido, Japan) at 4 °C overnight, followed by incubation with the corresponding secondary antibody conjugated with Alexa Fluor 350 (1:300; Life Technologies Inc, Grand Island, NY), Alexa Fluor 488 (1:500; Life Technologies Inc) and Alexa Fluor 594 (1:500; Life Technologies Inc) for 2 hours. Images were captured using a fluorescence microscope (Nikon Eclipse Ti; Technical Instruments). Immunohistochemical images were aligned with images captured during calcium imaging to determine the percentages of pruritogen-responsive DRG cells that were triple-labeled for SP, GRP, and VGLUT2.

3. Results

3.1. Electrophysiology

3.1.1. Chloroquine-evoked responses were inhibited more by antagonist co-application

A total of 210 chloroquine-responsive superficial dorsal horn neurons (78 NS, 73 WDR, 59 uncharacterized) were tested with spinal application of antagonists. The units were located in the superficial dorsal horn at a mean depth of 80.0 μ m \pm 4.8 (SEM) below the surface (Fig. 1K). All units had mechanosensitive receptive fields on the ipsilateral hind paw, and responded to i.d. microinjection of chloroquine within the receptive field. Fig. 1A shows an example of the prolonged response of a superficial dorsal horn unit to i.d. chloroquine. The graphs in Fig. 1C–H plot averaged neuronal responses, quantified as the mean firing rate averaged over the preceding 20-second period. Neuronal activity increased immediately following i.d. injection of chloroquine to a level that was significantly greater than the preinjection baseline (Fig. 1A–H). The mean chloroquine-evoked response was also significantly greater than saline (vehicle)-evoked responses in all treatment groups (C: vehicle group, $P = 0.004$ vs. pre; D: GRPR antagonist, $P = 0.0003$; E: NK-1 antagonist, $P = 0.001$; F: CNQX, $P = 0.026$; G: NK-1 + AMPA antagonist, $P = 0.0007$; H: all 3 antagonists, $P = 0.007$; unpaired t -test).

To investigate the role of SP, GRP, and glutamate as neurotransmitters that excite chloroquine-sensitive spinal neurons, one or more antagonists of these neurotransmitters was superfused over the spinal cord during the chloroquine-evoked response. In Fig. 1C, mean responses are aligned with the onset of vehicle superfusion (black bar) at time 0. Chloroquine-evoked firing usually peaked within the first few seconds postinjection and continued over the ensuing 120 seconds, allowing us to test the effect of antagonist superfusion during this period of activity. As a control, vehicle was superfused and shown to have no effect on chloroquine-evoked firing. Fig. 1A shows an individual example, and Fig. 1C shows that chloroquine-evoked firing rate remained significantly above baseline (Fig. 1C, *) during and after spinal superfusion of vehicle. Most units exhibited little or no adaptation in firing rate during the 60-second period of vehicle superfusion, while one

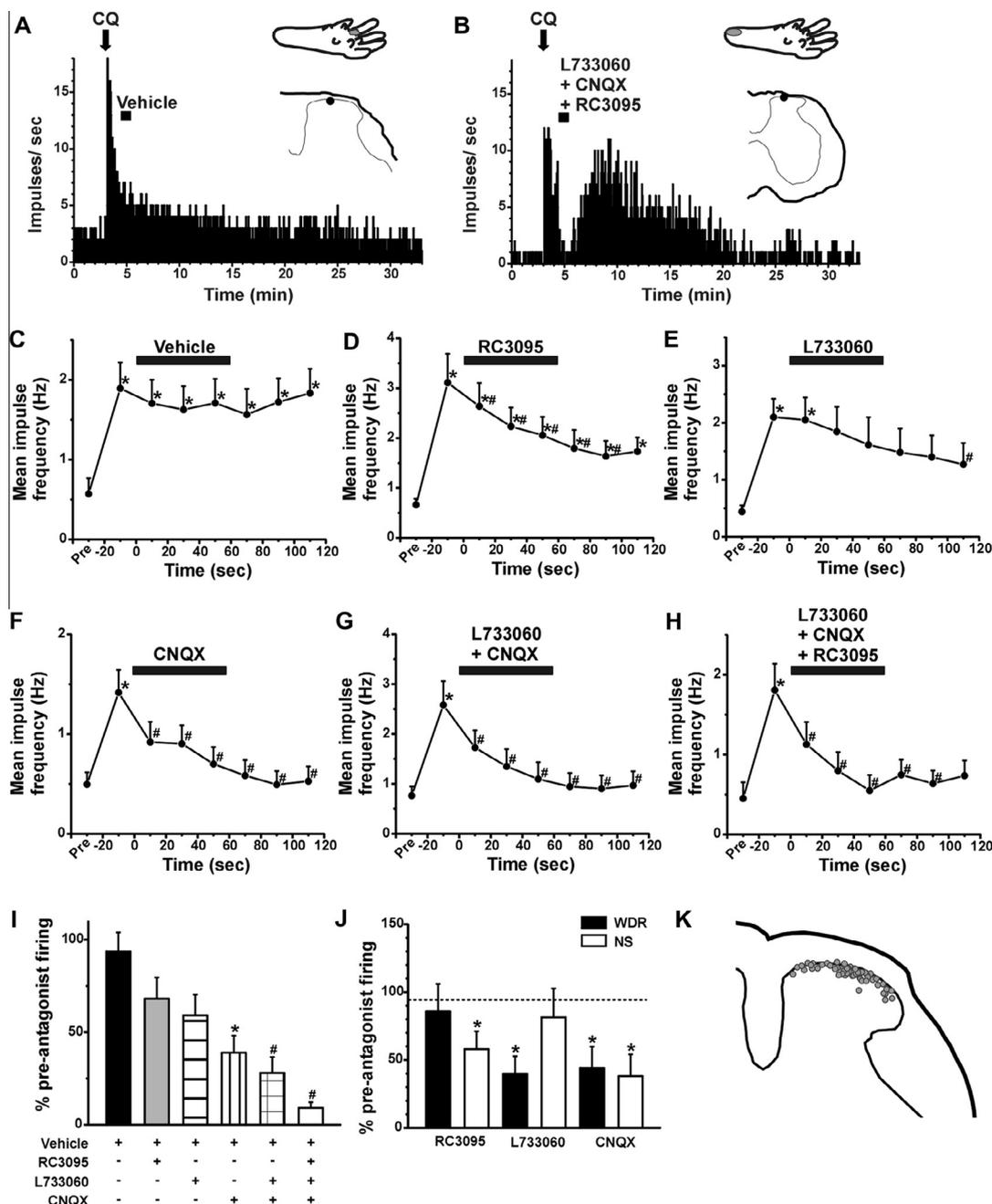


Fig. 1. Combined effects of neurokinin-1 (NK-1), gastrin-releasing peptide (GRP), and α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptor antagonists on intradermal (i.d.) chloroquine-evoked activity of superficial dorsal horn neurons. (A) Individual example (vehicle control). Peristimulus-time histogram (PSTH; bins: 1s) shows response of superficial dorsal horn neuron to i.d. chloroquine (at arrow). Chloroquine was injected i.d. in the hind paw receptive field area shown in the upper inset. Lower inset shows superficial recording site (dot). Vehicle (saline) was superfused over spinal cord (bar) during the initial part of the neuronal response to chloroquine. (B) As in (A) for a combination of NK-1, AMPA/kainate, and GRP receptor antagonists (PSTH for different superficial dorsal horn unit than in A). Chloroquine was injected i.d. (at arrow) in hind paw receptive field (upper inset). Shortly thereafter, a combination of NK-1, AMPA/kainate, and GRP receptor antagonists was superfused over the spinal cord (bar), resulting in marked suppression of chloroquine-evoked firing. (C) Vehicle control. Graph plots mean responses (impulse frequency averaged over 20 seconds) of superficial dorsal horn units before (Pre-) and after i.d. chloroquine. Graphs are aligned at time 0 with the onset of spinal superfusion (horizontal bar above graph). Time point -20 represents mean response following i.d. chloroquine, measured 20 seconds prior to onset of spinal superfusion. Error bars: SEM. *Significantly different compared to Pre ($P < 0.05$; Bonferroni test following one-way repeated-measures analysis of variance [ANOVA]). (D) GRP receptor antagonist RC-3095 (20 μ M). Format and symbols as in (C). #Significantly different compared to chloroquine-evoked response prior to spinal superfusion ($P < 0.05$; Bonferroni test following one-way repeated-measures ANOVA). (E) NK-1 receptor antagonist L-733060 (200 μ M). Format and symbols as in (C). (F) Glutamate receptor antagonist 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX) (100 μ M). Format and symbols as in (C). (G) Combined NK-1 and AMPA/kainate receptor antagonists. Format and symbols as in (C). (H) Combined NK-1, AMPA/kainate, and GRP receptor antagonists. Format and symbols as in (C). (I) Summary of antagonist effects. Bar graph plots mean responses during the 40–60-second period of spinal superfusion of vehicle (black bar), GRP receptor antagonist RC-3095 (gray bar), NK-1 antagonist L-733060 (horizontal striped bar), AMPA/kainate receptor antagonist CNQX (vertical striped bar), L-733060 + CNQX (checked bar), or RC-3095 + L-733060 + CNQX (white bar). All responses are normalized to the firing rate 20 seconds prior to vehicle or antagonist application. Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, one-way ANOVA, Bonferroni posttest. #Significantly different from vehicle group, $P < 0.01$, one-way ANOVA, Bonferroni post test, $n = 23$ –35/group. (J) Summary of antagonist effects for nociceptive-specific (NS) and wide dynamic range (WDR) cells. Bar graph plots mean responses of WDR (black bars) and NS units (white bars) during the 40–60-second period of spinal superfusion of, from left to right, RC-3095 (GRP receptor antagonist), L-733060 (NK-1 antagonist), or CNQX (AMPA/kainate receptor antagonist). All responses are normalized to the firing rate 20 seconds prior to vehicle or antagonist application. Dashed line: mean response during 40–60-second period of spinal superfusion of vehicle. Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, unpaired t -test, $n = 9$ –14/group. (K) Recording sites compiled on representative lumbar spinal cord section.

Table 1
Percentages of dorsal horn units that exhibited a decrease of 70% or more in firing rate following spinal superfusion of antagonists.

	VH	RC3095	L733060	CNQX	L733060 + CNQX	RC3095 + L733060 + CNQX
Chloroquine	0% (0/23)	24% (7/29)	30% (9/30)	58% (18/31)	71% (25/35)	85% (24/28)
Histamine	25% (4/16)	55% (10/18)	33% (6/18)	100% (14/14)		
AITC	27% (7/26)		22% (2/9)	62% (8/15)	89% (17/19)	

VH, Vehicle; CNQX, 6-cyano-7-nitroquinoxaline-2,3-dione; AITC, allyl isothiocyanate.

unit exhibited a decline of nearly 70%. Using this as a conservative criterion, 0/23 units tested exhibited a decline by more than 70% in the chloroquine-evoked firing rate relative to that observed prior to the spinal superfusion (Table 1).

Superfusion of the GRP receptor antagonist RC3095 resulted in an overall decline in mean firing rate (Fig. 1D). During spinal superfusion of RC3095, mean responses were still above prechloroquine baseline levels, but decreased significantly relative to the chloroquine-evoked response prior to spinal superfusion (Fig. 1D, #), indicating that the GRP receptor antagonist attenuated ongoing activity elicited by chloroquine. Twenty-four percent of units exhibited a decline of 70% or more during superfusion with the GRP antagonist (Table 1).

Chloroquine-evoked firing was also significantly attenuated after the cessation of superfusion with the NK-1 receptor antagonist L733060 (Fig. 1E, #), with 30% of units exhibiting a decline of 70% or more. Chloroquine-evoked firing was also significantly attenuated during and after spinal superfusion with the AMPA/kainate receptor antagonist CNQX (Fig. 1F), with 58% declining by 70% or more. Importantly, combinations of the NK-1 and AMPA/kainate receptor antagonist (Fig. 1G), or all 3 antagonists (Fig. 1B, H), significantly attenuated chloroquine-evoked firing during and after their spinal superfusion, with 71% and 85%, respectively, exhibiting reductions in firing rate of 70% or greater (Table 1). Fig. 1B shows an example in which spinal superfusion with all 3 antagonists completely suppressed chloroquine-evoked firing, followed by recovery of firing.

Fig. 1I summarizes the suppression of i.d. chloroquine-evoked neuronal firing by antagonists. Chloroquine-evoked firing during the 40–60-second period after onset of spinal superfusion was normalized to the firing rate 20 seconds prior to the superfusion, and these normalized values were compared with the firing rate 40–60-seconds after superfusion with vehicle. By this analysis, chloroquine-evoked firing was increasingly reduced by the GRPR, NK-1, and AMPA/kainate receptor antagonists applied individually, more strongly by the combination of NK-1 and AMPA/kainate antagonists, and most strongly by co-application of all 3 antagonists.

We additionally determined whether antagonists differentially affected dorsal horn neurons based on their subclassification as WDR or NS. Fig. 1J shows effects of the 3 antagonists on chloroquine-evoked responses of WDR ($n = 36$) and NS units ($n = 37$). The GRPR antagonist significantly reduced chloroquine-evoked firing in NS but not WDR cells. In contrast, the NK-1 antagonist significantly reduced chloroquine-evoked firing in WDR but not NS cells. CNQX significantly reduced chloroquine-evoked firing in both WDR and NS cells. It should be noted that the effects of antagonists were not related to whether the units additionally responded to histamine or not. Of the 75 chloroquine-responsive units that also responded to histamine, 42 were classified as NS cells and 33 as WDR. Of the units that responded to chloroquine but not histamine, 5 were NS and 5 were WDR.

3.1.2. CNQX alone inhibited histamine-evoked responses

The large majority of chloroquine-responsive units (75/85) also responded to i.d. injection of histamine. Following i.d. histamine, unit firing increased abruptly; an example is shown in Fig. 2A.

The graphs in Fig. 2C–F plot averaged neuronal responses to histamine, quantified as the mean firing rate averaged over the preceding 20-second period. In each instance, neuronal activity increased immediately following i.d. injection of histamine to a level that was significantly greater than the vehicle (saline)-evoked response (C: vehicle, $P = 0.018$ vs. pre; D: GRPR antagonist, $P = 0.011$; E: NK-1 antagonist, $P = 0.015$; F: CNQX, $P = 0.009$; unpaired t -test).

The individual example in Fig. 2B shows that spinal superfusion with CNQX completely suppressed histamine-evoked firing, as confirmed for the unit population (Fig. 2F) in which superfusion with CNQX significantly reduced the mean firing rate to the prehistamine baseline. Overall, CNQX significantly attenuated histamine-evoked firing to a level not different from that elicited by i.d. injection of vehicle (saline) (Fig. 2G, white bar), with 100% of units exhibiting a reduction in firing of more than 70% (Table 1). Both the GRPR and NK-1 antagonists numerically reduced histamine-evoked firing compared to vehicle (Fig. 2D, E, G), with 55% and 33% being reduced by more than 70%, respectively (Table 1). The overall effects, however, were not significantly different from vehicle (Fig. 2C).

Fig. 2H shows effects of the 3 antagonists on histamine-evoked responses of WDR ($n = 26$) and NS units ($n = 21$). Both NS and WDR unit responses to histamine were significantly reduced by CNQX (Fig. 2H). The GRP antagonist significantly reduced the mean histamine-evoked response of NS but not WDR units (Fig. 2H). The NK-1 antagonist failed to reduce histamine-evoked firing in either WDR or NS units.

3.1.3. Lack of effect of antagonists on baseline activity

There was no significant effect of any of the antagonists on the baseline activity of superficial dorsal horn neurons that were subsequently shown to respond to pruritogens. We compared the neuronal firing rate averaged over the 1-minute period prior to antagonist application with that during a comparable 1-minute period following application of the antagonist (before application of pruritic or noxious stimuli). Values prior to and after administration of each antagonist individually or in combination, are as follows. NK-1 antagonist L-733060: preapplication $0.88 \text{ Hz} \pm 0.23$ (SEM), postantagonist $0.72 \text{ Hz} \pm 0.19$ ($n = 10$). GRPR antagonist RC-3095: preapplication $0.54 \text{ Hz} \pm 0.54$, postantagonist: $0.53 \text{ Hz} \pm 0.53$ ($n = 4$). CNQX: preapplication $0.53 \text{ Hz} \pm 0.14$, postantagonist $0.64 \text{ Hz} \pm 0.21$ ($n = 22$). CNQX + L-733060: preapplication $0.52 \text{ Hz} \pm 0.17$, postantagonists $0.43 \text{ Hz} \pm 0.11$ ($n = 26$). CNQX + L-733060 + RC-3095: preapplication $0.14 \text{ Hz} \pm 0.06$, postantagonists $0.17 \text{ Hz} \pm 0.06$ ($n = 9$).

3.1.4. CNQX reduced firing elicited by AITC and noxious pinch

As a positive control, we wished to show that spinal superfusion with CNQX reduced responses of dorsal horn neurons to noxious stimuli as previously reported [22,26,28,44]. Topical AITC elicited a significant increase in firing of superficial dorsal horn neurons that declined slightly over the ensuing 2 minutes (Fig. 3A, C). The NK-1 receptor antagonist numerically reduced AITC-evoked firing (Fig. 3D, G). CNQX significantly reduced AITC-evoked firing (Fig. 3E, G; $P < 0.05$). Superfusion with both L733060 and CNQX further reduced AITC-evoked firing (Fig. 3B, F) to a level that was

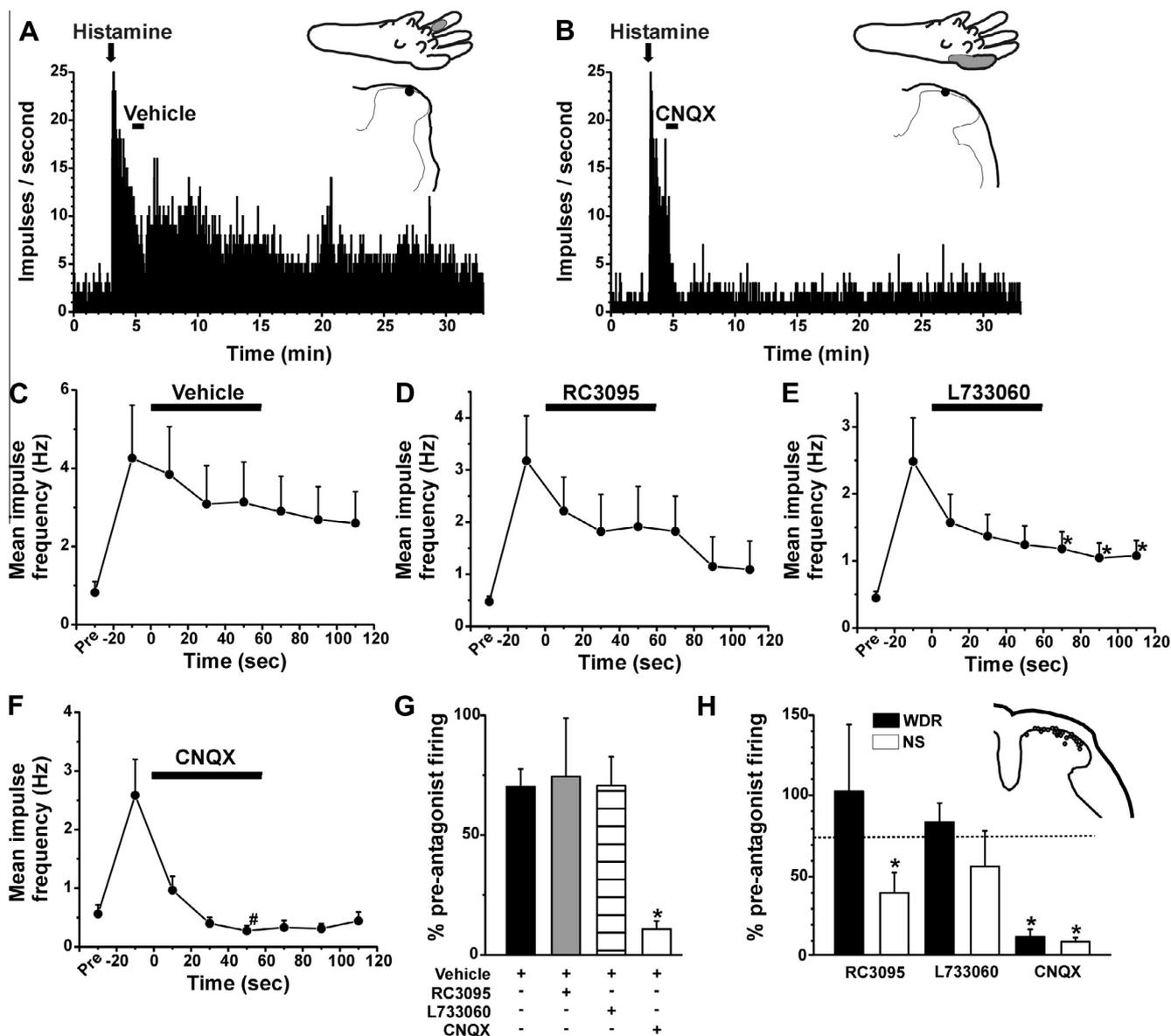


Fig. 2. Effects of neurokinin-1 (NK-1), gastrin-releasing peptide (GRP), and α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptor antagonist on intradermal (i.d.) histamine-evoked activity of superficial dorsal horn neurons. (A) Individual example (vehicle control). Peristimulus-time histogram (PSTH; bins: 1s) shows response of superficial dorsal horn neuron to histamine (at arrow) injected i.d. in the hind paw receptive field (upper inset). Lower inset shows superficial recording site (dot). Vehicle (saline) was superfused over spinal cord (bar) during the initial part of the neuronal response to histamine. (B) As in A for 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX) (PSTH for a different neuron than in A). Histamine was injected i.d. (at arrow) in hind paw receptive field (upper inset). Shortly thereafter, CNQX was superfused over the spinal cord (bar), resulting in marked suppression of histamine-evoked firing. (C) Vehicle controls. Graph plots mean responses (impulse frequency averaged over 20 seconds) of superficial dorsal horn units before (Pre-) and after i.d. histamine (format as in Fig. 1C). (D) As in C for spinal superfusion of GRP antagonist RC3095. (E) As in C for L-733060. *Significantly different compared to the pre ($P < 0.05$; Bonferroni test following one-way repeated-measures analysis of variance [ANOVA]). (F) As in C for CNQX. #Significantly different compared to histamine-evoked response prior to spinal superfusion ($P < 0.05$; Bonferroni test following one-way repeated-measures ANOVA). (G) Summary of antagonist effects. Bar graph plots, from left to right, the mean histamine-evoked responses during the 40–60-second period of spinal superfusion of vehicle (black bar), GRP receptor (GRPR) antagonist, RC-3095 (gray bar), NK-1R antagonist, L-733060 (horizontal striped bar) or AMPA/kainate receptor antagonist, CNQX (white bar). Responses are normalized to the firing rate before the antagonist application. Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, One-way ANOVA, Bonferroni posttest, $n = 14$ –18/group. (H) Summary of antagonist effects for nociceptive-specific (NS) and wide dynamic range (WDR) cells. Bar graph plots mean responses of WDR (black bars) and NS units (white bars) during the 40–60-second period of spinal superfusion of, from left to right, RC-3095 (GRPR antagonist), L-733060 (NK-1 antagonist) or CNQX (AMPA/kainate receptor antagonist). Dashed line indicates mean responses during the 40–60-second period of spinal superfusion of vehicle. All responses are normalized to the firing rate 20 seconds prior to vehicle or antagonist application. Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, unpaired t -test, $n = 6$ –10/group. Inset: Recording sites.

significantly different compared to either individual antagonist (Fig. 3F, G; $P < 0.001$ vs. vehicle).

We additionally tested the effects of these antagonists on spinal unit responses to noxious pinch. We tested chloroquine- and pinch-responsive units, as well as separate populations of NS and WDR units that were isolated by their response to pinch and that were unresponsive to i.d. chloroquine. A total of 22 units was

tested with the NK-1 antagonist (7 pinch + chloroquine responsive, 15 pinch but not chloroquine responsive), 39 with the AMPA/kainate antagonist (24 pinch + chloroquine-responsive, 15 pinch but not chloroquine responsive), and 45 with both antagonists (23 pinch + chloroquine responsive, 22 pinch but not chloroquine responsive). Effects of antagonists on pinch-evoked responses were very similar for chloroquine-responsive and -unresponsive units,

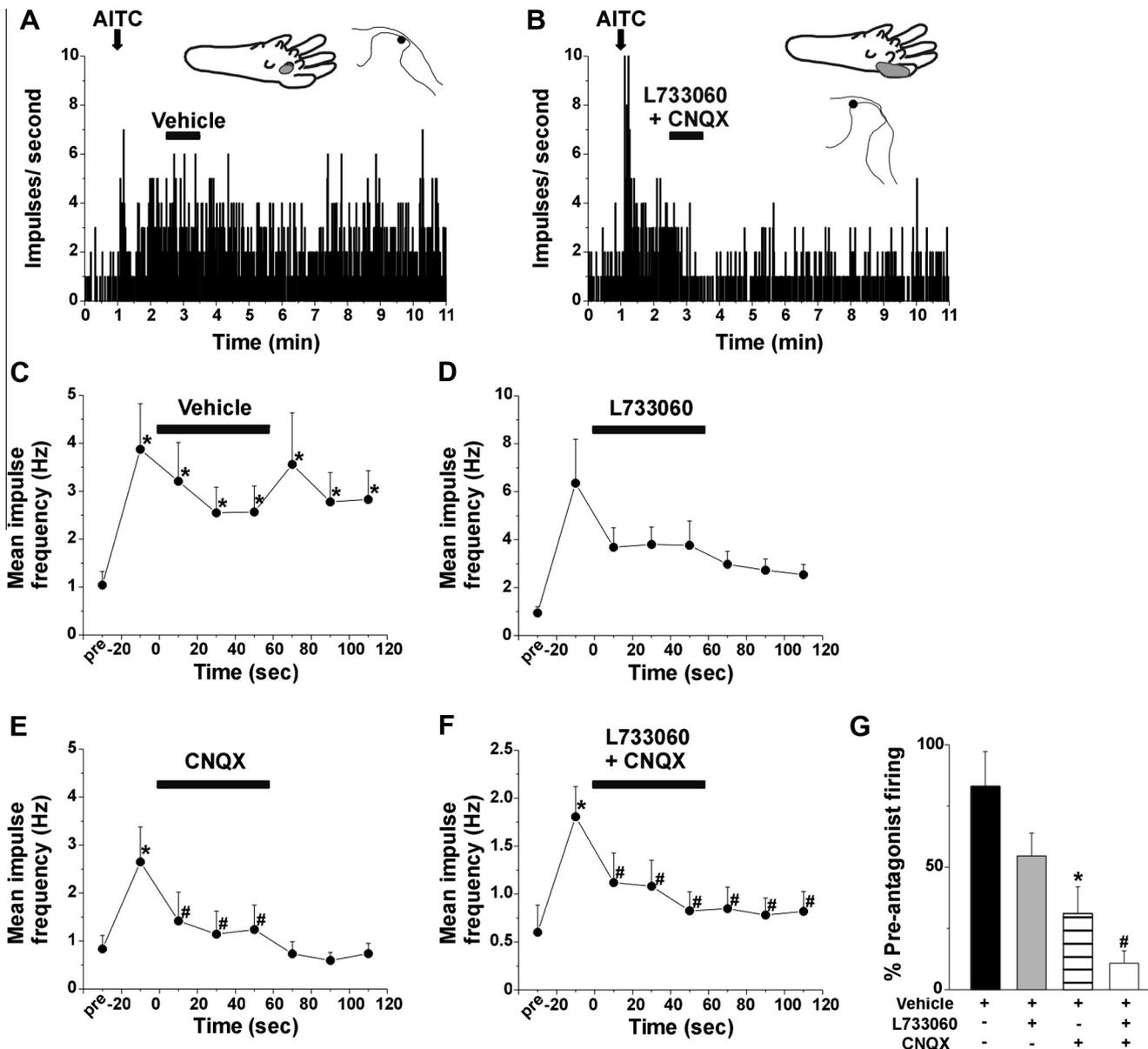


Fig. 3. Combined effects of neurokinin-1 (NK-1) and α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptor antagonists on topical allyl isothiocyanate (AITC)-evoked activity of superficial dorsal horn neurons. (A) Individual example shows peristimulus-time histogram (PSTH) of superficial dorsal horn unit's response to topical application of AITC to hind paw receptive field (upper left inset). Vehicle (saline) was superfused during AITC-evoked response. (B) As in (A) for different superficial dorsal horn neuron, with spinal superfusion of combined NK-1 (L733060) and AMPA/kainate (6-cyano-7-nitroquinoxaline-2,3-dione [CNQX]) receptor antagonists. (C) Vehicle control. Graph plots mean responses (impulse frequency averaged over 20 seconds) of superficial dorsal horn units before (Pre-) and after topical AITC (format as in Fig. 1C). Error bars: SEM. *Significantly different compared to Pre ($P < 0.05$; Bonferroni test following one-way repeated-measures analysis of variance [ANOVA]). (D) As in (C) for spinal superfusion of NK-1 receptor antagonist. (E) As in (C) for spinal superfusion of AMPA/kainate antagonist. #Significantly different compared to AITC-evoked response prior to spinal superfusion ($P < 0.05$; Bonferroni test following one-way repeated-measures ANOVA). (F) As in (C) for spinal superfusion of combined NK-1 and AMPA/kainate antagonists. #Significantly different compared to AITC-evoked response prior to spinal superfusion ($P < 0.05$; Bonferroni test following one-way repeated-measures ANOVA). (G) Summary of antagonist effects. Bar graph plots the mean AITC-evoked responses during the 40–60-second period of spinal superfusion of vehicle (black bar), NK-1 receptor antagonist (gray bar), AMPA/kainate receptor antagonist (horizontal striped bar), or combined NK-1 and AMPA/kainate receptor antagonists (white bar). Responses are normalized to the firing rate before the antagonist application. Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, one-way ANOVA, Bonferroni posttest, #significantly different from vehicle group, $P < 0.001$, one-way ANOVA, Bonferroni posttest, $n = 9–26$ /group.

and for NS and WDR units, so data were pooled. Noxious pinch elicited a transient robust increase in firing that was not reduced by the NK-1 receptor antagonist (Fig. 4A, B), but was significantly reduced by CNQX, followed 30 minutes later by recovery (Fig. 4C, D; $P < 0.001$). Co-application of the NK-1 antagonist and CNQX did not reduce the pinch-evoked response to any greater extent compared to CNQX alone (Fig. 4E, F; $P < 0.001$ vs. pre). Those data are consistent with previous studies [18,22,23,26,28,39,44].

3.2. Behavior

3.2.1. Chloroquine-evoked scratching was inhibited more by antagonist co-application

Intrathecal administration of each antagonist significantly attenuated chloroquine-evoked scratching (Fig. 5; $P < 0.005$). Co-administration of the NK-1 antagonist and CNQX attenuated chloroquine-evoked scratching to a greater extent than either

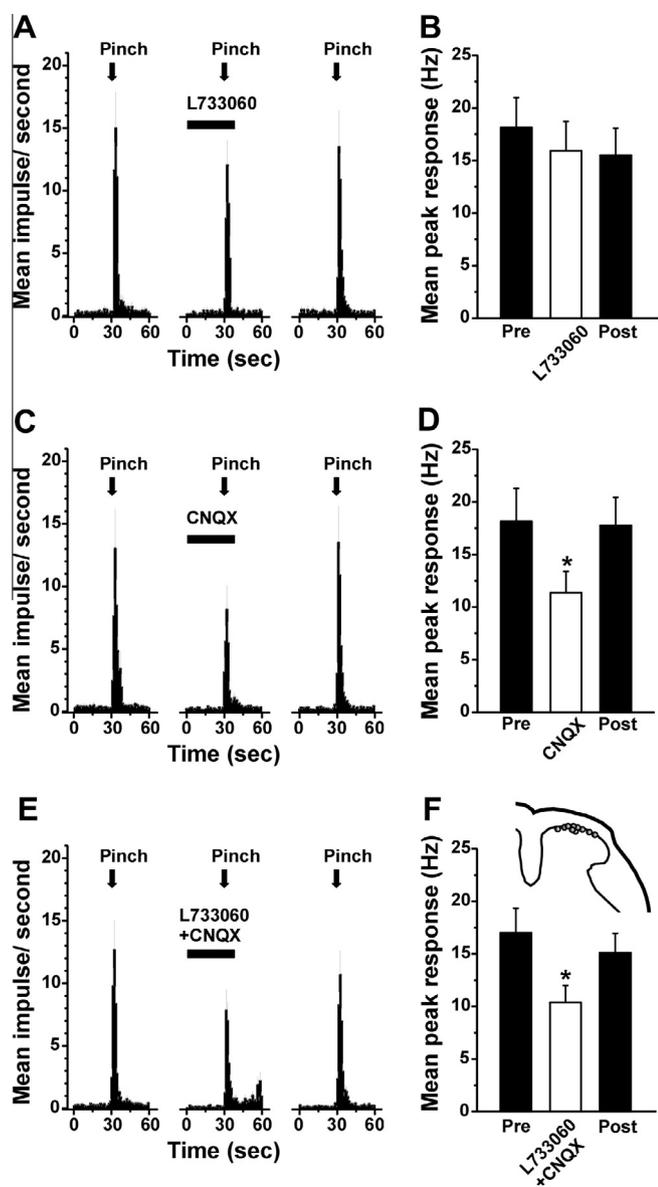


Fig. 4. Effects of neurokinin-1 (NK-1) antagonist, 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX), and both, on noxious pinch-evoked activity of superficial dorsal horn neurons. (A) Average responses to pinch. Averaged peristimulus-time histograms (PSTH) (bins: 1s) show, from left to right, the mean pinch-evoked responses before, during, and after the spinal superfusion of NK-1 receptor antagonist L733060. Error bars: SEM. $n = 22$ /group. (B) Summary of antagonist effects. Bar graph plots, from left to right, the mean pinch-evoked peak responses before (black bar), during (white bar), and after (black bar) the spinal superfusion of NK-1 receptor antagonist. $n = 22$ /group. (C) As in (A) for CNQX. Error bars: SEM. $n = 39$ /group. (D) As in (B) for CNQX. Error bars: SEM. *Significantly different from pre group, $P < 0.001$, one-way repeated-measures analysis of variance (ANOVA), Bonferroni posttest, $n = 39$ /group. (E) As in (A) for combined NK-1 antagonist and CNQX. Error bars: SEM. $n = 54$ /group. (F) As in (B) for combined NK-1 antagonist and CNQX. Error bars: SEM. *Significantly different from pre group, $P < 0.001$, one-way repeated-measures ANOVA, Bonferroni posttest, $n = 45$ /group. Inset above shows recording sites for units identified using pinch search stimulus.

antagonist individually (Fig. 5). Combined, the coapplication of all 3 antagonists (GRPR, NK-1, and AMPA) reduced scratching to an even greater extent compared to co-application of the NK-1 antagonist and CNQX (Fig. 5).

3.2.2. CNQX reduced histamine-evoked scratching behavior

Intrathecal administration of neither the NK-1 nor the GRPR antagonist attenuated histamine-evoked scratching (Fig. 6). In con-

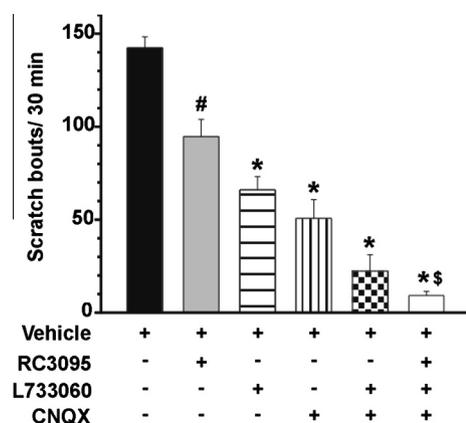


Fig. 5. Combined effects of intrathecally administered neurokinin-1 (NK-1), gastrin-releasing peptide (GRP), and α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptor antagonists on chloroquine-elicited scratching. Bar graph plots, from left to right, the mean number of scratch bouts/30 minutes elicited by intradermal (i.d.) chloroquine 5 minutes after prior intrathecal injection of vehicle (saline; black bar), the GRP receptor antagonist, RC-3095 (0.3 nmol; gray bar), the NK-1 antagonist, L-733060 (22.7 nmol; horizontal striped bar), the AMPA/kainate receptor antagonist, 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX; 20 nmol; vertical striped bar), L-733060 + CNQX (checked bar), or RC-3095 + L-733060 + CNQX (white bar). Error bars: SEM. *Significantly different from vehicle group, $P < 0.001$, one-way analysis of variance (ANOVA), Bonferroni posttest, $n = 6$ /group. #Significantly different from vehicle group, $P < 0.005$, one-way ANOVA, Bonferroni posttest, $n = 6$ /group. *Significantly different from CNQX group, $P < 0.05$, one-way ANOVA, Bonferroni posttest, $n = 6$ /group. Data for NK-1 (striped bar) and GRP receptor (gray bar) antagonists adapted from [9].

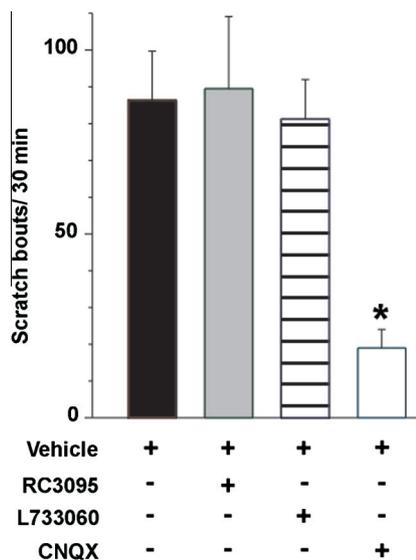


Fig. 6. Effect of intrathecally administered α -amino-3-hydroxy-5-methyl-4-isoxazole propionate acid (AMPA)/kainate receptor antagonist on histamine-elicited scratching. Bar graph plots, from left to right, the mean number of scratch bouts/30 minutes elicited by intradermal (i.d.) histamine 5 minutes after prior intrathecal injection of vehicle (saline; black bar), the gastrin-releasing peptide (GRP) receptor antagonist, RC-3095 (0.3 nmol; gray bar), the neurokinin-1 (NK-1) receptor antagonist, L-733060 (22.7 nmol; horizontal striped bar), or the AMPA/kainate receptor antagonist 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX; 20 nmol; white bar). Error bars: SEM. *Significantly different from vehicle group, $P < 0.05$, one-way analysis of variance, Bonferroni post test, $n = 6$ /group. Data for effects of NK-1 (striped bar) and GRP receptor antagonist (gray bar) adapted from [9].

trast, the number of histamine-evoked scratch bouts was significantly decreased by CNQX (Fig. 6; $P < 0.05$) to a level that did not differ from that elicited by i.d. injection of vehicle (10.1 ± 4.0 ; $P = 0.202$ unpaired t -test) [5].

3.3. Cell imaging

3.3.1. Calcium imaging of DRG cells

Of a total of 898 DRG cells imaged, 8.4% responded to chloroquine and 12.9% responded to histamine, consistent with previous studies [2,9,32,56]. Fig. 7A shows examples of 2 DRG cells that responded to chloroquine but not histamine.

3.3.2. Immunofluorescent labeling of pruritogen-responsive DRG cells

Following calcium imaging, the DRG cells were fixed and triple-immunostained for SP, GRP, and VGLUT2. A total of 597 DRG cells were labeled. Fig. 7B–E shows immunostained DRG cells from the calcium imaging experiment shown in Fig. 7A; the 2 chloroquine-responsive cells in (A) are indicated by yellow circles. Fig. 7B shows GRP-immunopositive DRG cells (green). Fig. 7C shows DRG cells immunopositive for SP (blue), including one of the chloroquine-responsive cells exhibiting weak immunoreactivity. Fig. 7D shows cells immunopositive for VGLUT2 (red), including one of the chloroquine-responsive cells. The merged view in Fig. 7E shows

cells that were triple-labeled (magenta; arrows) for VGLUT2, SP, and GRP.

Overall, 27.1% of all DRG cells examined were immunopositive for SP, 23.8% for GRP, and 79.2% for VGLUT2, consistent with previous studies [9,12,15,20,42,49,52]. Of the DRG cells that responded to chloroquine, 16%, 18%, and 80% were immunopositive for SP, GRP, and VGLUT2, respectively (Fig. 7F). Of the histamine-responsive cells, 10%, 17.5%, and 77% were immunopositive for SP, GRP, and VGLUT2, respectively (Fig. 7G). All of the histamine-responsive cells that were immunopositive for either SP or GRP were also immunopositive for VGLUT2 (Fig. 7G). Fig. 7H shows the incidence of immunostaining of DRG cells that responded to both chloroquine and histamine; more cells co-expressed GRP (21%) than SP (7%). Fig. 7I similarly shows the incidence of immunostaining of DRG cells that responded to chloroquine but not histamine, of which GRP and SP were approximately equally co-expressed (GRP 17%; SP 22%). Fig. 7J shows the incidence of immunostaining of DRG cells that responded to histamine but not chloroquine. Of these cells, SP was predominantly expressed (15%) compared to GRP (4%).

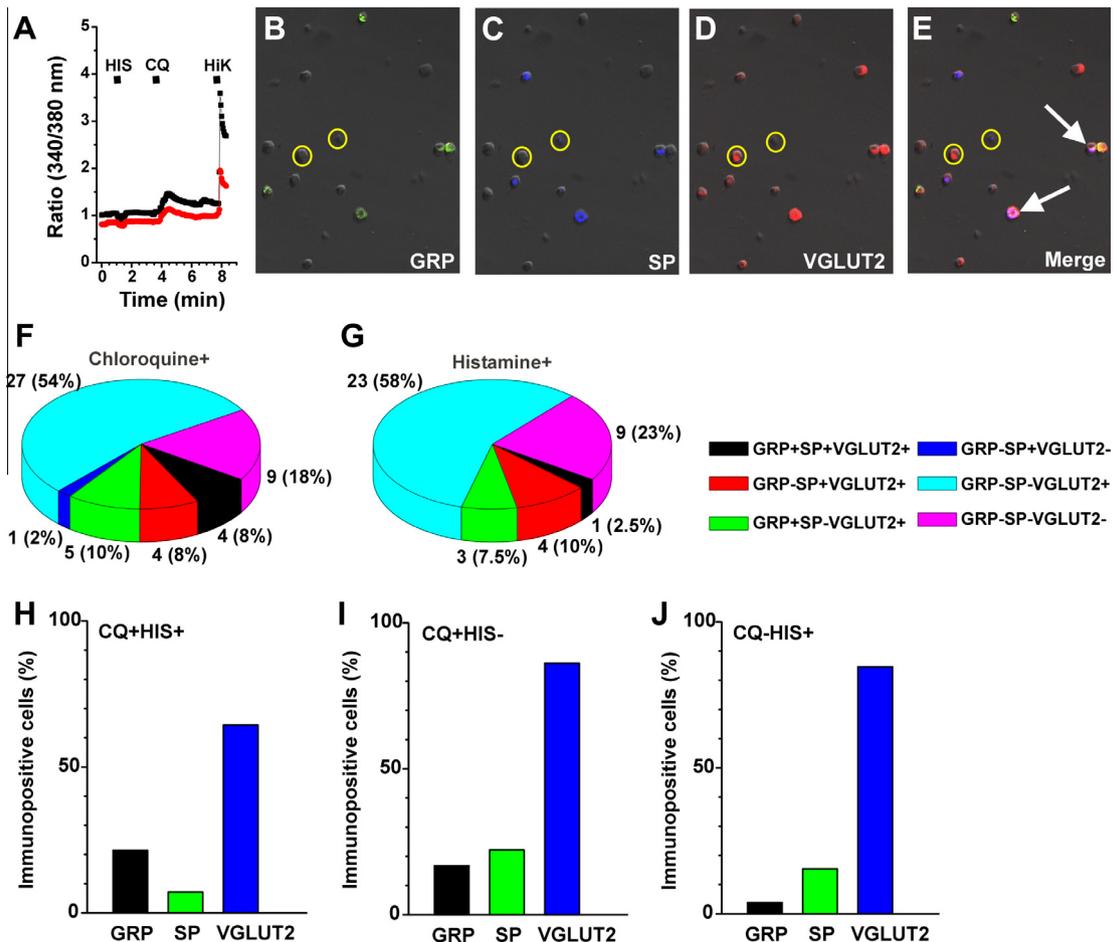


Fig. 7. Pruritogen-responsive dorsal root ganglion (DRG) cells double- and triple-labeled for substance P (SP)-, gastrin-releasing peptide (GRP)-, and vesicular glutamate transporter type 2 (VGLUT2)-immunoreactivity. (A) Graph plots 340/380 nm ratio as a function of time for 2 cells (encircled in yellow in B–E) that responded to chloroquine but not histamine. Black bars indicate time of application of each indicated chemical. (B) Fluorescence microscopic image of DRG cell labeled for GRP (green) following calcium imaging. Chloroquine-sensitive cells were not labeled with GRP. (C) SP (blue). One chloroquine-sensitive cell (right) was lightly labeled. (D) VGLUT2 (red). One-chloroquine-responsive cell (left) was labeled for VGLUT2. (E) Triple-staining (Merge). Two cells indicated by arrows were triple-labeled for GRP, SP, and VGLUT2. (F) Pie chart summarizing the percentages of chloroquine-responsive DRG cells (assessed by calcium imaging) that were co-labeled for SP, GRP, and/or VGLUT2 (n = 50). (G) As in (F), summarizing percentages of histamine-responsive DRG cells (assessed by calcium imaging) that were co-labeled for SP, GRP, and/or VGLUT2 (n = 40). Legend to the right of pie chart applies to both (F) and (G). (H) Incidence of DRG cells that responded to both chloroquine and histamine (assessed by calcium imaging) that were co-labeled for SP, GRP, and/or VGLUT2 (n = 14). (I) As in (H), for DRG cells that responded to chloroquine but not histamine (n = 36). (J) As in (H), (I) for DRG cells that responded to histamine but not chloroquine (n = 26).

4. Discussion

The present findings imply that nonhistaminergic itch is mediated by the combined intraspinal release of glutamate, SP, and GRP from chloroquine-sensitive pruriceptors to activate itch-signaling spinal neurons. In contrast, histamine-mediated itch depends primarily on glutamate, with GRP playing a lesser role in NS neurons. These conclusions are supported by the following: (1) Chloroquine-evoked responses were partially suppressed by each individual antagonist and completely inhibited by co-application; CNQX alone abolished histamine-evoked responses; (2) Behavioral studies provided comparable results; (3) 10–18% of chloroquine- or histamine-sensitive DRG neurons co-expressed substance P or GRP, while ~80% co-expressed VGLUT2. These data support the concept of co-administration of AMPA/kainate, NK-1, and GRPR antagonists to treat antihistamine-resistant chronic itch. The NK-1 antagonist aprepitant shows promise for chronic itch [48]. An AMPA antagonist (Perampanel) is U.S. Food and Drug Administration-approved for epilepsy, and a GRPR antagonist shows promise in treating cancer [45]. Future clinical trials are needed to determine the efficacy and side effects of combined antagonist treatment for chronic itch.

4.1. Chloroquine-responsive dorsal horn neurons in itch

MrgprA3-expressing afferents responded to chloroquine, histamine, capsaicin, and other noxious stimuli [26], similar to the present and previously recorded [8] dorsal horn neurons. Chloroquine acts at MrgprA3 expressed in primary afferent C fibers [31], although we cannot exclude the possibility that chloroquine activates mast cells or keratinocytes to release substances that indirectly affect other afferent fibers. In mice lacking the capsaicin-sensitive ion channel TRPV1 (transient receptor potential V1 channel), TRPV1 was selectively re-expressed in MrgprA3-expressing DRG neurons [26]. In these animals, i.d. injection of capsaicin, which normally elicits nocifensive wiping behavior, instead elicited hind limb scratching indicative of itch [26]. This implies that MrgprA3-expressing primary afferent fibers are linked to a “labeled line” itch pathway, regardless of what type of stimulus activates them. Accordingly, we speculate that the chloroquine-responsive dorsal horn neurons recorded in our study contribute to neural circuits selectively mediating itch and scratching behavior.

A subpopulation of histamine-sensitive, chloroquine-insensitive dorsal horn neurons, not studied at present, may also participate in histaminergic itch. Most chloroquine-responsive neurons also responded to histamine. Histamine-responsive dorsal horn neurons also responded to SLIGRL-NH2 [8], which acts at PAR-2 and MrgprC11 [33]. Knockout mice lacking MrgprA3 exhibited reduced scratching to chloroquine but not histamine [31], while a more recent study reported that ablation of MrgprA3-expressing sensory neurons attenuated scratching elicited by histamine, chloroquine, and other itch mediators [26]. The latter results support the argument that histaminergic itch is mediated by the presently reported population of chloroquine-sensitive spinal dorsal horn neurons. While this appears inconsistent with the differential effect of the GRPR antagonist to reduce chloroquine- but not histamine-evoked neuronal firing, we speculate that these 2 itch mediators elicit different patterns of spinal neurotransmitter release (see below). Alternatively, a small subpopulation of histamine-sensitive, chloroquine-insensitive neurons not recorded in this study may be critical for glutamate-mediated histaminergic itch transmission. This is consistent with a recent report that histamine and chloroquine, respectively, activated separate populations of TRPV1- or TRPA1-expressing pruriceptors [40].

4.2. Spinal neurotransmitters mediating histaminergic and nonhistaminergic itch

Chloroquine-evoked scratching and spinal neuronal firing was reduced by individually applied GRPR, NK-1 (except for NS neurons), or AMPA antagonists, and was abolished by their co-application. One interpretation is that GRP, SP, and glutamate are released from intraspinal terminals of chloroquine-sensitive pruriceptors to excite itch-signaling dorsal horn neurons (Fig. 8A). Consistent with this, chloroquine-sensitive DRG cells co-expressed GRP, SP, and VGLUT2. In contrast, CNQX inhibited histamine-evoked neuronal responses, with the NK-1 and GRPR antagonists having lesser or no effect, implicating glutamate as the primary spinal neurotransmitter for histaminergic itch.

Most chloroquine-responsive neurons also responded to histamine. It is novel that responses of the same neuron to chloroquine and histamine were pharmacologically distinct. Chloroquine- and histamine-sensitive pruriceptors are functionally distinct subpopulations and might release different neurotransmitters [40]. Chloroquine excitation of NS neurons was reduced by NK-1 and AMPA antagonists (Fig. 1J), implying input primarily from pruriceptors that release SP and glutamate, that is, chloroquine-sensitive, histamine-insensitive (CQ+HIS-), and chloroquine-insensitive histamine-sensitive (CQ-HIS+) DRG cells (Fig. 8A). Chloroquine excitation of WDR neurons was reduced by GRPR and AMPA antagonists, implying input from pruriceptors that release GRP (ie, CQ+HIS+ and CQ+HIS-; Fig. 8A). Histamine excitation of both WDR and NS cells was inhibited by CNQX, implying input from histamine-sensitive pruriceptors (ie, CQ-HIS+ and CQ+HIS+). That the GRPR antagonist partly inhibited responses of NS (but not WDR) neurons (Fig. 1J) implies input from chloroquine- and histamine-sensitive (CQ+HIS+) DRG cells containing GRP (Fig. 8A). The lack of effect of the NK-1 antagonist on histamine-evoked responses implies that NS and WDR neurons either do not receive input from cells that co-express SP (CQ-HIS+), or that they do, but SP participates exclusively in a peripheral role such as the axon reflex induced by histamine [43].

Alternatively, different firing patterns of primary afferents might account for the pharmacologically distinct effects of chloroquine and histamine. MrgprA3-expressing sensory neurons exhibited distinct firing patterns (bursting vs steady state) to different itch mediators [27] that may determine if glutamate and/or neuropeptide are released from the presynaptic terminal.

Another possibility is that NS and WDR neurons receive inputs from different populations of interneurons using different neurotransmitters (Fig. 8B). Nppb released from central terminals of primary afferents excites GRPR-expressing spinal interneurons to account for all pruritogen-evoked scratching behavior in mice [38]. Our data are not inconsistent with this, since SP, GRP, and glutamate are expressed in spinal interneurons [51,54]. It is currently unknown if i.d. chloroquine and histamine excite separate interneuronal populations that release different neurotransmitters.

We confirmed expression of SP in a subpopulation of chloroquine-sensitive DRG cells [9]. However, most MrgprA3-expressing sensory neurons co-expressed calcitonin gene-related peptide and IB-4, but not SP [27]. Chloroquine-evoked scratching was reduced by ~70% in mice lacking MrgprA3 [27]; residual scratching may be mediated by SP-expressing, MrgprA3-negative neurons. Presumably, SP is released by a small subpopulation of nonhistaminergic pruriceptors [47]. In contrast, NK-1 antagonists failed to inhibit histamine-evoked scratching or neuronal firing, even though SP was expressed in some histamine-sensitive chloroquine-insensitive DRG neurons. That all neuropeptide-expressing histamine-sensitive DRG neurons co-expressed VGLUT2 suggests

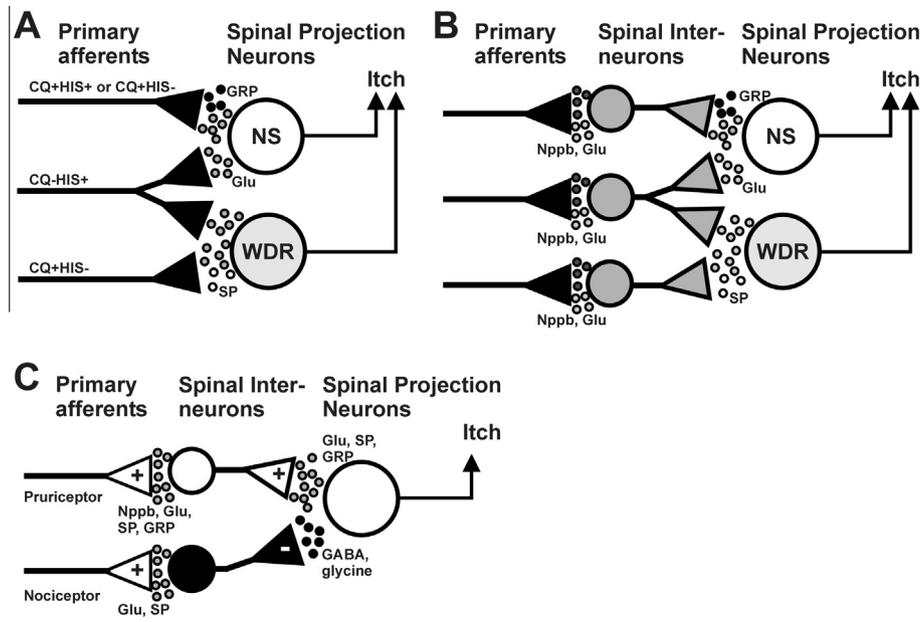


Fig. 8. Schematic diagram showing primary afferents and spinal dorsal horn neurons that transmit itch. (A) Different pruriceptors release differing proportions of glutamate (Glu) and neuropeptides gastrin-releasing peptide (GRP) or substance P (SP) to excite nociceptive-specific (NS) and/or wide dynamic range (WDR) neurons that signal itch. ●: GRP; ○: SP; ⊙: Glutamate. (B) Pruriceptors release natriuretic polypeptide B (Nppb) and possibly glutamate to excite second-order spinal interneurons, which in turn release differing proportions of GRP, SP and glutamate to excite itch-signaling NS and/or WDR neurons. See text for further explanation. ●: GRP; ○: SP; ⊙: Glutamate; ⊚: Natriuretic polypeptide B (Nppb). (C) Schematic of excitatory and inhibitory spinal interneurons. Itch mediators excite pruriceptors that may release glutamate and/or neuropeptides such as Nppb, GRP, or SP. Intrathecal 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX) inhibits glutamatergic transmission from pruriceptors and/or excitatory spinal interneurons to itch-signaling neurons. Nociceptors release glutamate and SP to excite inhibitory spinal interneurons, which inhibit itch-signaling spinal neurons. Loss of vesicular glutamate transporter type 2 (VGLUT2) in nociceptive afferents leads to reduced excitation of the inhibitory interneurons to disinhibit itch. This effect is proposed to outweigh any reduction in input from primary afferent pruriceptors.

that glutamate is the main neurotransmitter released by histamine-sensitive pruriceptors. Consistent with this, electrical stimulation of dorsal roots evoked responses in histamine-sensitive spinal neurons that were abolished by CNQX [29].

We confirm that GRP was coexpressed by some chloroquine-sensitive neurons [9]. Chloroquine-evoked scratching and neuronal firing were reduced by the GRPR antagonist, which did not affect histamine-evoked scratching (but reduced responses of NS neurons). Activity in the unaffected WDR neurons may have compensated for inhibition of NS neurons to account for the lack of GRPR antagonist effect on scratching.

The specificity of the GRP antibody and presence of GRP within DRG neurons has been questioned [36], although GRP mRNA and protein were reported to be expressed in substantial populations of primary sensory neurons [9,10,25,30,32,34–36,49,52]. However, GRP staining of the rhizotomized spinal cord revealed that most GRP is synthesized locally [25]. Thus, GRP may be released primarily by spinal interneurons (Fig. 8B) rather than (or in addition to) pruriceptive afferents. In this scenario, spinal neurons sensitive to GRP may be synaptically excited by glutamate, rather than GRP released from primary afferents [29].

Prurigen-responsive DRG neurons expressed VGLUT2, implying that pruriceptors release glutamate. Knockout mice lacking VGLUT2 in primary afferents exhibited reduced nociception and enhanced scratching, explained by decreased release of glutamate from nociceptors and reduced excitation of inhibitory spinal interneurons, thereby disinhibiting itch-signaling neurons [30,36,41]. Fig. 8C shows a balance of excitatory pruriceptive and inhibitory interneuronal inputs onto itch-signaling spinal neurons. We speculate that knockout of VGLUT2 more strongly reduces nociceptive than pruriceptive afferent drive, shifting the balance toward enhanced itch transmission. Antagonism of spinal AMPA receptors more strongly blocks direct and indirect (via excitatory interneurons)

glutamatergic pruriceptive input, shifting the balance toward reduced itch transmission.

4.3. Spinal nociceptive transmission

Noxious thermal, mechanical, and chemical stimuli evoked spinal release of SP [24], which elicited prolonged excitatory postsynaptic potentials [14,53] that were inhibited by an NK-1 antagonist [18]. Spinal neurons exhibiting prolonged mechanically evoked excitatory postsynaptic potentials received more synaptic contacts by SP-immunoreactive varicosities [19]. Spinal neuronal responses to formalin and capsaicin were inhibited by NK-1 antagonists [14,23,39]. The NK-1 antagonist inhibited dorsal neuronal responses to AITC, but not to noxious pinch, consistent with previous studies [18,23,37,39]. Mice with genetic ablation of nonpeptidergic MrgprD-expressing sensory neurons exhibited reduced behavioral responses to noxious mechanical but not thermal stimuli, suggesting a role for nonpeptidergic sensory neurons in mechanical nociception [13].

Glutamate is generally associated with spinal nociceptive transmission. Spinal neuronal responses to pinch and AITC were reduced or blocked by CNQX in this study, consistent with previous studies [22,26,28,44]. Our results indicate that spinal pathways signaling itch and pain likely share glutamate and SP as excitatory neurotransmitters. This is consistent with previous studies showing that most pruritogen-sensitive spinal neurons also respond to algogens, suggesting that the central nervous system discriminates between itch and pain based on input from partially overlapping subpopulations of itch- and pain-signaling neurons [3,4,7,16,17].

Conflict of interest statement

None of the authors declares any conflict of interest.

Acknowledgements

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