

Gi-protein-coupled 5-HT_{1B/D} receptor agonist sumatriptan induces type I hyperalgesic priming

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Abstract

We have recently described a novel form of hyperalgesic priming (type II) induced by agonists at two clinically important Gi-protein-coupled receptors (Gi-GPCRs), mu-opioid and A1-adenosine. Like mu-opioids, the antimigraine triptans, which act at 5-HT_{1B/D} Gi-GPCRs, have been implicated in pain chronification. We determined whether sumatriptan, a prototypical 5-HT_{1B/D} agonist, produces type II priming. Characteristic of hyperalgesic priming, intradermal injection of sumatriptan (10 ng) induced a change in nociceptor function such that a subsequent injection of prostaglandin-E₂ (PGE₂) induces prolonged mechanical hyperalgesia. However, onset to priming was delayed 3 days, characteristic of type I priming. Also characteristic of type I priming, a protein kinase C_ε, but not a protein kinase A inhibitor attenuated the prolongation phase of PGE₂ hyperalgesia. The prolongation of PGE₂ hyperalgesia was also permanently reversed by intradermal injection of cordycepin, a protein translation inhibitor. Also, hyperalgesic priming did not occur in animals pretreated with pertussis toxin or isolectin B4-positive nociceptor toxin, IB4-saporin. Finally, as observed for other agonists that induce type I priming, sumatriptan did not induce priming in female rats. The prolongation of PGE₂ hyperalgesia induced by sumatriptan was partially prevented by coinjection of antagonists for the 5-HT_{1B} and 5-HT_{1D}, but not 5-HT₇, serotonin receptors and completely prevented by coadministration of a combination of the 5-HT_{1B} and 5-HT_{1D} antagonists. Moreover, the injection of selective agonists, for 5-HT_{1B} and 5-HT_{1D} receptors, also induced hyperalgesic priming. Our results suggest that sumatriptan, which signals through Gi-GPCRs, induces type I hyperalgesic priming, unlike agonists at other Gi-GPCRs, which induce type II priming.

Keywords: Hyperalgesic priming, Hyperalgesia, 5-HT_{1B} receptor, 5-HT_{1D} receptor, GPCRs, Chronic pain, Triptans

1. Introduction

Although the mechanism underlying the transition from acute to chronic pain remains poorly understood, it has been suggested that some analgesics can produce pain chronification. Thus, opioids, which are used clinically to treat moderate-to-severe pain, especially agonists at the mu-opioid receptor (MOR), may come to exacerbate or actually produce pain during their chronic administration, a phenomenon referred to as opioid-induced hyperalgesia (OIH).^{6,60,63} Similarly, the triptan class of drugs, used to treat migraine,^{25,35,76} also facilitates pain chronification and/or contributes to migraine chronification, a condition referred to as medication overuse headache (MOH).^{9,11,26,28,38,41,45,77} The target for the therapeutic effect of triptans is believed to be 5-HT_{1B} and 5-HT_{1D} receptors that, like MOR, are inhibitory G-protein-coupled receptors (Gi-GPCRs).^{37,42,64,86,95,96} Therefore, in this study, we explored the possibility that, like MOR and A1-adenosine receptor agonists,^{7,8} triptans would also induce type II hyperalgesic priming. In addition, we explored the 5-HT

receptor subtypes at which triptans act (5-HT_{1B}, 5-HT_{1D}, and 5-HT₇) to induce priming. We report that although sumatriptan, a prototypical 5-HT_{1B/D} receptor agonist, induces hyperalgesic priming, this priming meets the criteria for type I rather than type II priming.

2. Methods

2.1. Animals

Experiments were performed on 230-g to 280-g male and female Sprague-Dawley rats (Charles River Laboratories, Hollister, CA). Rats were housed in a controlled environment in the animal care facility at the University of California, San Francisco, under a 12-hour light/dark cycle. Food and water were available ad libitum. The experimental protocols were approved by the Institutional Animal Care and Use Committee at UCSF and adhered to the guidelines of the American Association of Laboratory Animal Care, the National Institutes of Health (NIH), and the Committee for Research and Ethical Issues of the International Association for the Study of Pain (IASP), for the use of animals in research. In the design of experiments, all efforts were made to minimize the number of animals used and their suffering.

2.2. Mechanical nociceptive threshold testing

Mechanical nociceptive threshold was quantified using an Ugo Basile Analgesymeter (Randall-Selitto paw-withdrawal test; Stoelting, Chicago, IL), which applies a linearly increasing mechanical force to the dorsum of the rat's hind paw, as previously described.^{32,78,80} Nociceptive threshold was defined

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

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as the force in grams at which the animal withdrew its paw; baseline paw-pressure nociceptive mechanical threshold was defined as the mean of the 3 readings taken just before a test agent was injected. Each paw was treated as an independent measure and each experiment performed on a separate group of rats. Data are presented as mean change from baseline mechanical nociceptive threshold.

2.3. Drugs and their administration

The chemicals used in this study were cordycepin 5'-triphosphate sodium salt (protein translation inhibitor^{7,8,34}), prostaglandin-E₂ (PGE₂, a hyperalgesic agent that acts at receptors on nociceptors to sensitizes them), sumatriptan succinate (a 5-HT_{1B} and 5-HT_{1D} receptor agonist), CP-93129 dihydrochloride hydrate (a 5-HT_{1B} receptor agonist), pertussis toxin (PTX) (Gi-protein inhibitor), and SB-269970 (a 5-HT₇ receptor antagonist), all from Sigma-Aldrich (St. Louis, MO); PKCεV₁₋₂ (PKCε-I, a protein kinase Cε (PKCε)-specific translocation inhibitor peptide^{7,8,48,58}), from Calbiochem (La Jolla, CA); H-89 dihydrochloride (inhibitor of protein kinase A [PKA]^{7,8}) from Santa Cruz Biotechnology (Dallas, TX); L-694,247 (a 5-HT_{1D} receptor agonist), BRL 15572 (a 5-HT_{1D} receptor antagonist), and NAS-181 (a 5-HT_{1B} receptor antagonist), all from Tocris Bioscience (Avonmouth, Bristol, United Kingdom).

The selection of doses was based on previous studies that showed their effectiveness when injected intradermally on the dorsum of the hind paw.^{3,7,8,32,52} The stock solution of PGE₂ (1 μg/μL) was prepared in 10% ethanol and additional dilutions made with physiological saline (0.9% NaCl), yielding a final ethanol concentration of less than 1%. Cordycepin, sumatriptan, CP-93129, PTX, PKCεV₁₋₂, and SB-269970 were dissolved in saline. All other drugs were dissolved in 100% DMSO (Sigma-Aldrich) and further diluted in saline containing 2% Tween 80 (Sigma-Aldrich). The final concentration of DMSO and Tween 80 was 2%. All drugs were injected intradermally on the dorsum of the hind paw, in a volume of 5 μL, using a 30-gauge hypodermic needle adapted to a 50-μL Hamilton syringe (Reno, NV). The injection of cordycepin, H-89, PKCεV₁₋₂, and PTX was preceded by a hypotonic shock (2 μL of distilled water, separated by a bubble of air to avoid mixing in the same syringe), to facilitate the entry of compounds into the nerve terminal.^{14,16}

2.4. Intrathecal administration of IB4-saporin or SSP-saporin

2.4.1. IB4-saporin

Isolectin B4 (IB4)-saporin, an IB4-positive nociceptor neurotoxin (Advanced Targeting Systems, San Diego, CA), was diluted in saline, and a dose of 3.2 μg, in a volume of 20 μL, was administered intrathecally, 14 days before the priming experiments. The dose of IB4-saporin and time protocol were chosen based on previous reports from us and other groups.^{7,8,51,52,66,89}

2.4.2. SSP-saporin

The neurotoxin [Sar⁹,Met(O₂)¹¹] substance P-saporin (SSP-saporin; Advanced Targeting Systems, San Diego, CA) was diluted in saline, and a dose of 100 ng, in a volume of 20 μL, was administered intrathecally, 14 days before the priming experiments. The addition of [Sar⁹,Met(O₂)¹¹] to substance P (SP) conjugated to saporin makes the agent more stable and

potent than when SP is bound to saporin. The dose and pretreatment interval that we used were based on previous reports,^{22,93} which demonstrated the effectiveness of this agent to deplete SP-containing fibers with no loss of lumbar dorsal horn neurons expressing the neurokinin 1 (NK1) receptor in deeper laminae and prominent loss of NK1 receptor in laminae I.^{56,59,87,92}

Rats were briefly anesthetized with 2.5% isoflurane (Phoenix Pharmaceuticals, St. Joseph, MO) in 97.5% O₂. Then, a 30-gauge hypodermic needle was inserted, on the midline, into the subarachnoid space, between the L4 and L5 vertebrae. The control treatment consisted of intrathecal injection of saline (vehicle, 20 μL). Animals regained consciousness approximately 1 minute after removal from the anesthetic chamber. There was no effect of IB4-saporin or SSP-saporin on the mechanical nociceptive threshold per se.

2.5. Sumatriptan-induced changes in nociceptor function

Our group has previously shown that a single intradermal injection of a selective 5-HT₁ receptor agonist produced mechanical hyperalgesia (Fig. 1A).^{2,79,81} To investigate the changes in nociceptor function produced by the injection of sumatriptan (a 5-HT_{1B/1D} receptor agonist, 10 ng), 5-HT_{1B} receptor agonist (CP-93129, 10 or 100 ng) or 5-HT_{1D} receptor agonist (L-694,247, 10 or 100 ng)—measured as prolonged response to a hyperalgesic mediator, at a point in time when the mechanical nociceptive threshold was not different from presumatriptan baseline-PGE₂ (100 ng), was injected at the same site, and the change in nociceptive threshold evaluated 30 minutes and 4 hours later. The presence of hyperalgesia at the fourth hour is characteristic of priming.^{4,7,8,31} To evaluate the intracellular signaling pathways that play a role in priming induced by sumatriptan and to investigate the mechanisms that play a role in the induction of the changes in nociceptor function produced by the activation of the 5-HT_{1B/D} receptor, pharmacological agents were injected before sumatriptan (prevention protocol). To investigate the second messengers involved in the expression of the neuroplasticity, inhibitors were administered before the injection of PGE₂ in the already primed paw (inhibition protocol), at a time when mechanical nociceptive threshold was not different from presumatriptan levels.

2.6. Statistics

In all experiments, the dependent variable was mechanical paw-withdrawal threshold, expressed as percentage change from baseline. The average paw-withdrawal thresholds before the injection of sumatriptan and before the tests with PGE₂ (3 or more days, depending on the experiment) were 123.0 ± 1.05 g and 123.3 ± 1.12 g, respectively; paired Student *t* test showed no significant difference between these values (*t*₁₂₅ = 0.4285, *P* = 0.6753). The total number of paws used in this study was 126. To compare the mechanical hyperalgesia induced by injection of the neuroplasticity-inducing agents (ie, sumatriptan, 5-HT_{1B} [CP-93129], or 5-HT_{1D} [L-694,247] receptor agonists) and to compare the effect of PGE₂ in different groups, in the presence or absence of inhibitors of signaling pathways, two-way repeated-measures analysis of variance, followed by Bonferroni post hoc test, was performed. Graph Pad Prism 5.0 (GraphPad Software, Inc, San Diego, CA) was used to plot graphs and to perform statistical analyses; a *P* value less than 0.05 was considered statistically significant. Data are presented as mean ± SEM.

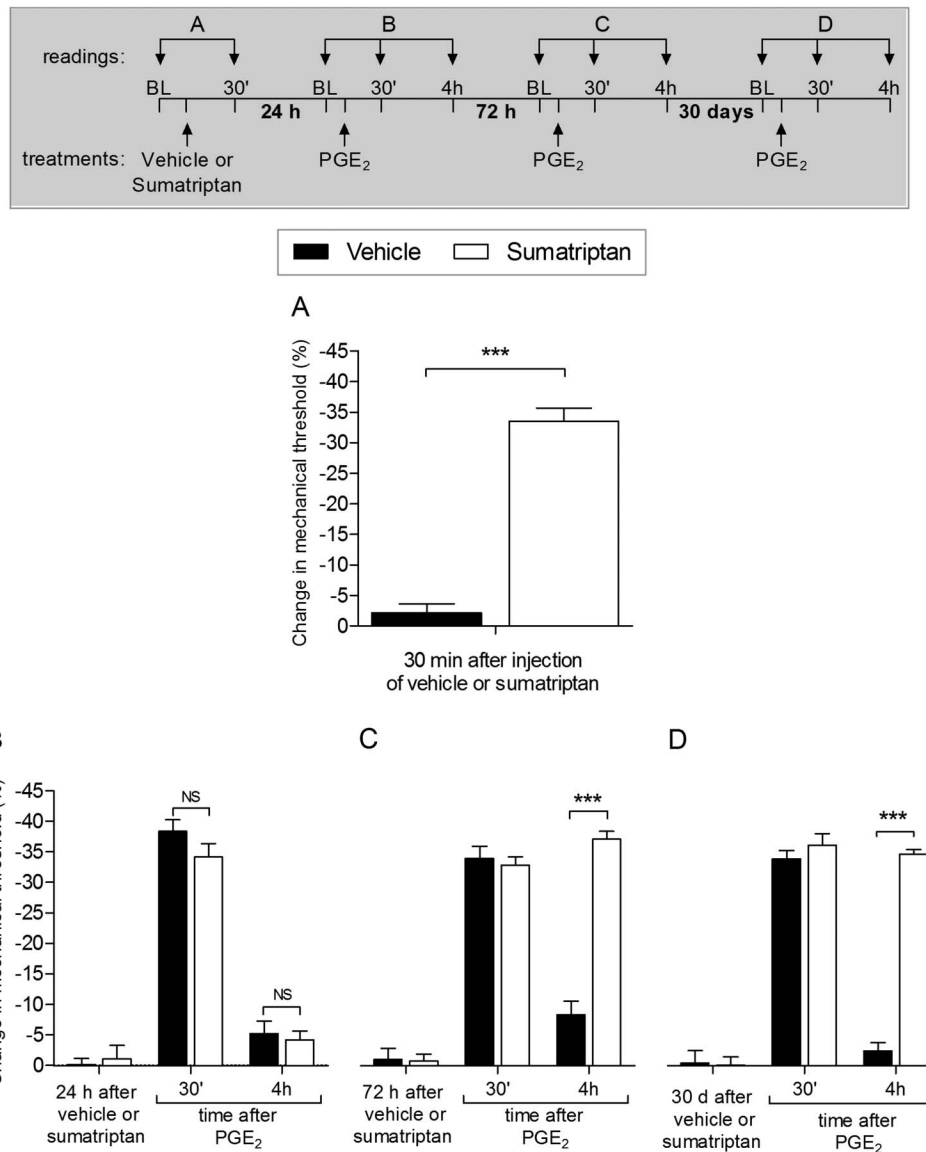


Figure 1. Sumatriptan induces mechanical hyperalgesia and hyperalgesic priming in male rats. (A) Rats were treated with a single intradermal injection of vehicle (5 μ L; black bar) or sumatriptan (10 ng in 5 μ L; white bar), and 30 minutes later, mechanical nociceptive threshold was evaluated by the Randall–Selitto paw-withdrawal test. The group treated with sumatriptan showed significant mechanical hyperalgesia, when compared with the group treated with vehicle ($***P < 0.0001$; unpaired Student t test), indicating that sumatriptan produces a pronociceptive effect. Average mechanical nociceptive threshold before the injection was 126.2 ± 2.7 g, for vehicle, and 118.5 ± 1.5 g, for sumatriptan group. (B) Twenty-four hours later, when the mechanical nociceptive threshold was no longer different from preinjection baseline (BL) ($t_5 = 1.667$; $P = 0.1942$, for the vehicle group; $t_5 = 0.2116$; $P = 0.8460$, for the sumatriptan group; paired Student t test), prostaglandin E₂ (PGE₂) (100 ng) was injected intradermally at the same site on the dorsum of the hind paw, and mechanical nociceptive threshold evaluated 30 minutes and 4 hours later. In both groups, PGE₂ induced significant hyperalgesia at 30 minutes, which was no longer present at the fourth hour, in the both groups (not significant (NS), $P > 0.05$, when both groups are compared; two-way repeated-measures analysis of variance (ANOVA) followed by Bonferroni post hoc test), indicating that hyperalgesic priming was not present 24 hours after the injection of vehicle or sumatriptan. However, 72 hours later (C) and 30 days later (D), when PGE₂ (100 ng) was again injected, at the same site, hyperalgesia induced by PGE₂ was present 30 minutes after injection in the group previously treated with sumatriptan and was still present at the fourth hour ($F_{1,20} = 72.97$, $***P < 0.0001$, when both groups are compared at the fourth hour; two-way repeated-measures ANOVA followed by Bonferroni post hoc test). These data demonstrate that a single injection of sumatriptan, 72 hours or 30 days before, produced long-term changes in nociceptor function characteristic of hyperalgesic priming (N = 6 paws per group).

3. Results

3.1. Sumatriptan-induced hyperalgesic priming

One of the defining features of both type I and II priming is the prolongation of hyperalgesia induced by pronociceptive mediators, prototypically PGE₂.^{4,12,33,57,69,73} To determine whether sumatriptan induces hyperalgesic priming, we injected PGE₂ intradermally, at the site of nociceptive testing. We report that a single low dose of sumatriptan (10 ng) induces mechanical

hyperalgesia (Fig. 1A). This differs from the pronociceptive effects of MOR and A1-adenosine agonists that took repeated administration before they induced hyperalgesia.^{7,8} Therefore, in the following experiments, we tested for priming after a single administration of sumatriptan. Unlike type II priming, in which the prolongation of PGE₂ hyperalgesia is observed immediately after the repeated injections of MOR or A1-adenosine receptor agonists, no prolongation of PGE₂ hyperalgesia was observed when PGE₂ was administered 24 hours after sumatriptan

(Fig. 1B). However, when it was injected 72 hours (Fig. 1C) or 30 days (Fig. 1D) after sumatriptan, we observed prolonged hyperalgesia. This demonstrates the time course for the onset of priming to be similar to that observed for type I hyperalgesic priming.^{4,12}

3.2. Role of 5-HT_{1B} and 5-HT_{1D} receptors in sumatriptan-induced priming

Since triptans are agonists at two Gi-GPCRs, 5-HT_{1B} and 5-HT_{1D},^{5,24,35,39,43,82,84} we evaluated the ability of antagonists at these two receptors to prevent sumatriptan-induced

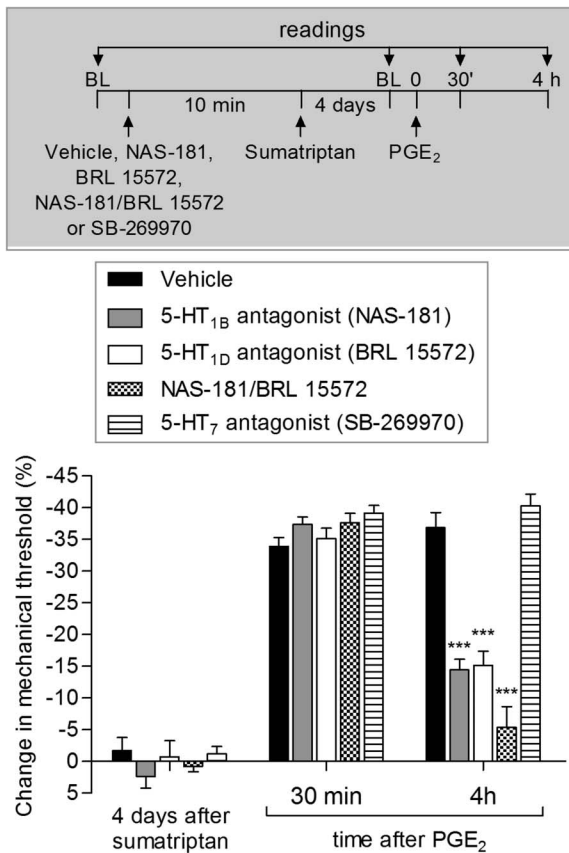


Figure 2. Role of 5-HT_{1B} and 5-HT_{1D}, but not 5-HT₇, receptors in sumatriptan-induced prolongation of prostaglandin E₂ (PGE₂)-induced hyperalgesia. Male rats received vehicle (5 μ L; black bars), NAS-181 (1 μ g; 5-HT_{1B} antagonist; gray bars), BRL 15572 (1 μ g; 5-HT_{1D} antagonist; white bars), the combination of NAS-181 (1 μ g)/BRL 15572 (1 μ g; dotted bars), or SB-269970 (1 μ g; 5-HT₇ antagonist; horizontally striped bars) on the dorsum of the hind paw. Ten minutes later, sumatriptan (10 ng) was injected at the same site. Four days later, when the mechanical nociceptive thresholds were not different from presumatriptan injection control baseline (BL) ($t_5 = 0.8165$; $P = 0.4740$, for the vehicle group; $t_5 = 1.260$; $P = 0.2967$, for the NAS-181 group; $t_5 = 0.3015$; $P = 0.7827$, for the BRL 15572 group; $t_5 = 1.000$; $P = 0.3910$, for the NAS-181/BRL 15572 group; and $t_5 = 1.667$; $P = 0.1942$, for the SB-269970 group; paired Student t test), PGE₂ (100 ng) was injected at the same site, and the mechanical nociceptive threshold evaluated. In all groups of rats evaluated 30 minutes after its injection, PGE₂ induced significant hyperalgesia. However, in the groups previously treated with NAS-181 (gray bars) or BRL 15572 (white bars), the prolongation of PGE₂-induced hyperalgesia was significantly attenuated and completely eliminated in the group previously treated with the combination of NAS-181/BRL 15572 (dotted bars; $F_{2,30} = 507.75$; $***P < 0.0001$, when NAS-181, BRL 15572, and NAS-181/BRL 15572 groups are compared with the vehicle-treated group; two-way repeated-measures analysis of variance followed by Bonferroni post hoc test), indicating the participation of both 5-HT_{1B} and 5-HT_{1D}, but not 5-HT₇, receptors in the induction of hyperalgesic priming by sumatriptan (N = 6 paws per group).

hyperalgesic priming. We found that, although alone the 5-HT_{1B} and 5-HT_{1D} receptor antagonists (NAS-181 and BRL 15572, respectively) each partially attenuate the magnitude of the prolongation of PGE₂ hyperalgesia (Fig. 2, gray and white bars), the coadministration of the two antagonists completely prevented sumatriptan-induced prolongation of PGE₂ hyperalgesia (Fig. 2, dotted bars). Because it has been suggested that triptans also produce some of their effects by action at the 5-HT₇ receptor,^{71,75,88,90,91} we also determined whether a 5-HT₇ receptor antagonist (SB-269970) would attenuate sumatriptan-induced priming. We found that the SB-269970 did not attenuate sumatriptan-induced priming (Fig. 2, horizontally striped bars).

3.3. Direct activation of 5-HT_{1B} and 5-HT_{1D} receptors induces hyperalgesic priming

We found that the prolongation of PGE₂-induced hyperalgesia by injection of sumatriptan (10 ng) is dependent of activation of both 5-HT_{1B} and 5-HT_{1D} receptors (Fig. 2). Therefore, we next tested the effect of selective agonists for 5-HT_{1B} (CP-93129; Fig. 3, gray bars) and 5-HT_{1D} (L-694,247; Fig. 3, white bars). We observed that the dose of 100 ng, but not 10 ng, of both agonists induced priming as manifest by prolongation of PGE₂-induced hyperalgesia (Fig. 3).

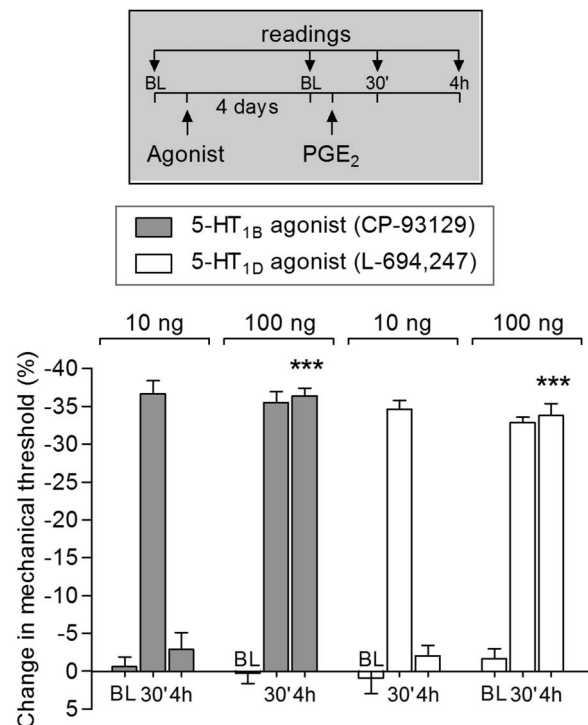


Figure 3. Agonists for 5-HT_{1B} and 5-HT_{1D} receptors induced hyperalgesic priming. Male rats were injected intradermally with agonists for 5-HT_{1B} (CP-93129, 10 or 100 ng; gray bars) or 5-HT_{1D} (L-694,247, 10 or 100 ng; white bars) receptors. Four days later, prostaglandin E₂ (PGE₂) (100 ng) was injected at the same site, and the mechanical nociceptive threshold was evaluated 30 minutes and 4 hours after its injection. In all groups of rats, PGE₂ induced significant hyperalgesia, evaluated 30 minutes after injection. Also, we observed prolongation of PGE₂-induced hyperalgesia in the groups previously treated with 100 ng of agonist for 5-HT_{1B} ($F_{1,20} = 94.06$, $***P < 0.0001$) and 5-HT_{1D} ($F_{1,20} = 127.07$, $***P < 0.0001$; two-way repeated-measures analysis of variance followed by Bonferroni post hoc test showed) receptor, when the fourth hour of the groups was compared. BL: baseline (N = 6 paws per group).

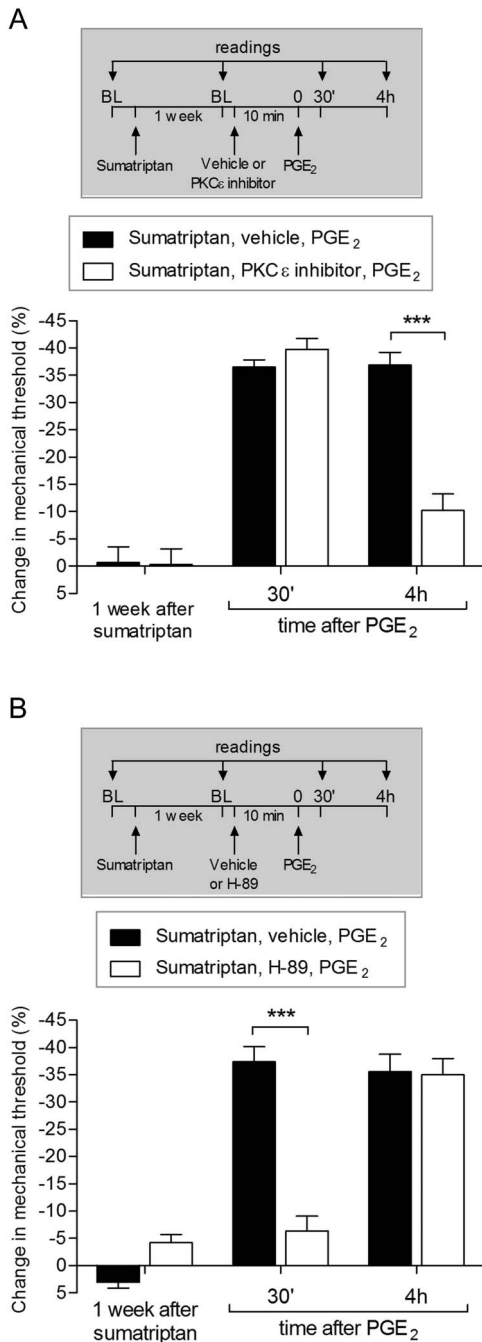


Figure 4. Protein kinase Cε (PKCε) but not protein kinase A (PKA) plays a role in the expression of hyperalgesic priming induced by sumatriptan. (A) Male rats received a single injection of sumatriptan (10 ng) on the dorsum of the hind paw. One week later, when the mechanical nociceptive thresholds were not different from presumatriptan injection baseline (BL) ($t_5 = 0.3203$; $P = 0.7697$, for black bars; $t_5 = 0.2089$; $P = 0.8479$, for white bars; paired Student *t* test), prostaglandin E₂ (PGE₂) (100 ng) was injected at the same site, in the presence of vehicle (control, black bars) or PKCε inhibitor (1 μg, white bars). The mechanical nociceptive threshold was then evaluated 30 minutes and 4 hours later, by Randall–Selitto paw-withdrawal test. In both groups, PGE₂ induced significant hyperalgesia, evaluated 30 minutes after injection. However, we observed significant attenuation of PGE₂-induced prolongation of hyperalgesia in the group previously treated with PKCε inhibitor ($F_{1,15} = 132.58$, $***P < 0.0001$, when the vehicle and PKCε inhibitor group were compared; two-way repeated-measures analysis of variance (ANOVA) followed by Bonferroni post hoc test). (B) A different group of male rats was primed with an intradermal injection of sumatriptan (10 ng), and 1 week later, received at the same site, vehicle (5 μL) or a PKA inhibitor (H-89; 1 μg). Ten minutes later, PGE₂ (100 ng) was injected on the dorsum of the hind paw and the mechanical nociceptive thresholds were evaluated 30 minutes and 4 hours later. Although

3.4. Protein kinase Cε dependence in expression of sumatriptan-induced priming

Another mechanism that distinguishes type I from type II priming is the second messengers mediating the prolongation of PGE₂ hyperalgesia, PKCε for type I priming^{4,70} and PKA for type II.^{7,8} Compatible with the above findings, which support the suggestion that sumatriptan induces type I priming, we observed that the prolongation of PGE₂ hyperalgesia induced by sumatriptan was attenuated by a PKCε (Fig. 4A), but not by a PKA (Fig. 4B) inhibitor.

3.5. Peripheral protein translation dependence of sumatriptan-induced priming

A third distinction between type I and type II priming is the dependence of type I³⁰ but not type II^{7,8} priming, on protein translation in the peripheral terminal of the primary afferent nociceptor. We report that intradermal injection of cordycepin, an inhibitor of protein translation, permanently reversed sumatriptan-induced priming (Fig. 5), further suggesting that sumatriptan induces type I priming.

3.6. Role of the inhibitory G-protein α_i subunit in sumatriptan-induced priming

Because the 5-HT_{1B} and 5-HT_{1D} receptors are Gi-GPCRs,^{37,42,64,86,95,96} to determine the signaling pathway downstream of the 5-HT_{1B/D} receptor that contributes to the prolongation of PGE₂-induced hyperalgesia, we tested the effect of the treatment with the G-protein α_i subunit inhibitor, PTX, injected before sumatriptan. We found that the prolongation of PGE₂-induced hyperalgesia was inhibited by PTX (Fig. 6). Of note, the ability of PTX to inhibit the induction of sumatriptan-induced priming (Fig. 6), the expression of type II priming induced by A1-adenosine receptor agonist CPA⁸ and also type I hyperalgesic priming^{29,33,57} contrasts with MOR agonist DAMGO-induced type II priming where PTX failed to inhibit the prolongation of PGE₂-induced hyperalgesia induced by DAMGO.⁷

3.7. IB4-positive nociceptor dependence of sumatriptan-induced priming

We have previously demonstrated that the induction of type I priming is prevented by spinal intrathecal treatment with IB4-saporin, a neurotoxin that eliminates IB4-positive nociceptors,^{7,8,51,52,66,89} whereas type II priming induction by the MOR agonist DAMGO is prevented by intrathecal administration of a stabilized form of SP, conjugated to saporin (SSP-saporin; unpublished results), a specific neurotoxin that destroys neurons with processes containing NK1 receptors in the superficial but not the deeper laminae of the dorsal horn,^{22,59,62,93} by eliminating SP-containing sensory neurons. In the present experiments, we found that, in rats pretreated with IB4-saporin but not with SSP-saporin, the injection of sumatriptan did not induce prolongation of PGE₂ hyperalgesia, evaluated 4 days later (Fig. 7).

PGE₂-induced hyperalgesia was still present after 30 minutes, in the group that received vehicle, in the group treated with H-89, it was significantly attenuated. However, it was present at the fourth hour ($F_{2,12} = 132.95$, $***P < 0.0001$, when vehicle and H-89 groups are compared at 30 minutes; two-way repeated-measures ANOVA followed by Bonferroni post hoc test), indicating that the expression of priming induced by previous injection of sumatriptan is not dependent on PKA (N = 6 paws per group).

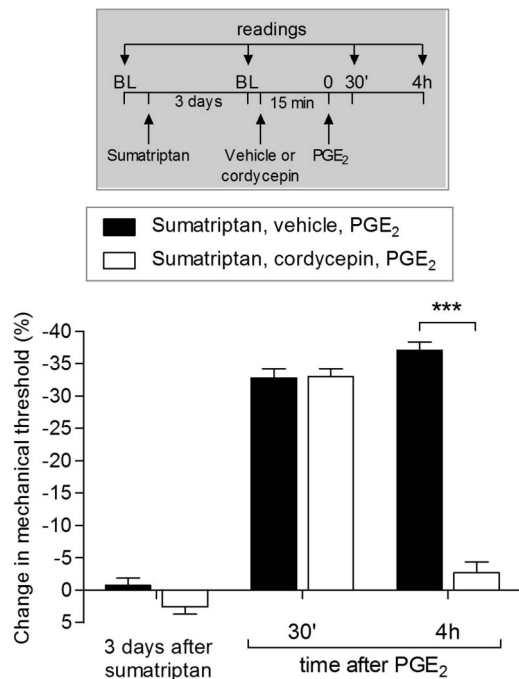


Figure 5. Hyperalgesic priming induced by sumatriptan is dependent on local protein translation. Male rats that were treated with intradermal injection of sumatriptan (10 ng) on the dorsum of the hind paw received, 3 days later, prostaglandin E₂ (PGE₂) (100 ng) injected at the same site, in the presence of vehicle (5 μ L, black bars) or the inhibitor of protein translation, cordycepin (1 μ g, white bars), administered 15 minutes before. Mechanical nociceptive threshold was evaluated 30 minutes and 4 hours after injection of PGE₂. Although the hyperalgesia induced by PGE₂ was present 30 minutes after injection in the group previously treated with cordycepin, it was significantly inhibited at the fourth hour ($F_{1,15} = 104.94$, $***P < 0.0001$, when both groups are compared at the fourth hour; two-way repeated-measures analysis of variance followed by Bonferroni post hoc test). BL: baseline (N = 6 paws per group).

3.8. Sexual dimorphism in sumatriptan-induced priming

We have previously shown that the administration of agonists for cell-surface receptors (such as tumor necrosis factor- α , Monocyte Chemoattractant Protein-1 (MCP-1), and interleukin-6) induces type I priming only in male rats.⁵³ In contrast, induction of type II priming by Gi-GPCR agonists is observed in females and also in males.^{7,8} In this study, we observed that sumatriptan did not induce priming in female rats (**Fig. 8**), another characteristic feature of type I hyperalgesic priming.⁵³

4. Discussion

The triptans, agonists at serotonin 5-HT_{1B} and 5-HT_{1D} receptors, are an important class of drugs used in the treatment of migraine.^{1,35,36,40,47,55,84} One limitation in their clinical use is that they can contribute to migraine chronification and more frequent episodes of headache, a condition referred to as MOH, recently characterized as a global epidemic.^{9,11,27,28,38,41,45,77} Both of the triptan receptors are Gi-protein coupled, which they share with other classes of analgesics, including those that act at MOR or cannabinoid receptors (CB).^{67,74} Importantly, opioids can also produce exacerbation of the pain for which they are clinically administered,^{21,23,44,60,65} a phenomenon referred to as OIH. We have studied OIH, using a model in the primary afferent nociceptor hyperalgesic priming (type II).^{7,8} Therefore, in the present experiments, we determined whether sumatriptan, a clinically used triptan,^{35,36,49,83} would also induce type II priming.

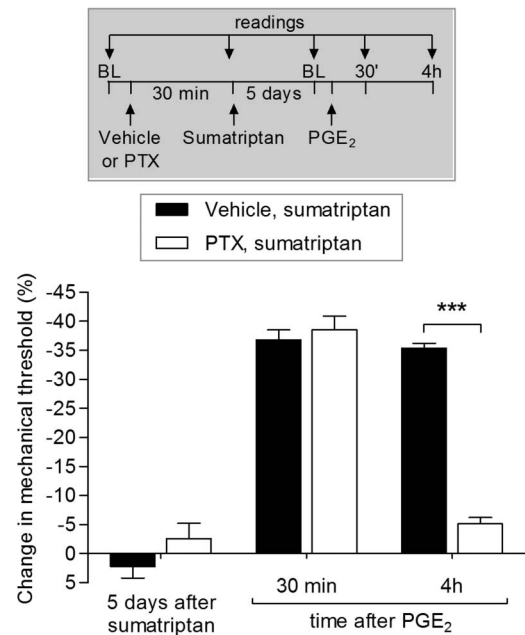


Figure 6. Role of G-protein α subunit in sumatriptan-induced priming. Male rats were treated with vehicle (5 μ L, black bars) or pertussis toxin (PTX; 1 μ g, white bars) by intradermal injection, and 30 minutes later, sumatriptan (10 ng) was injected at the same side. Five days later, prostaglandin E₂ (PGE₂) (100 ng) was injected intradermally at the same site on the dorsum of the hind paw, and the mechanical hyperalgesia was evaluated 30 minutes and 4 hours later, by Randall–Selitto paw-withdrawal test. In both groups, PGE₂ induced significant hyperalgesia, evaluated 30 minutes after injection. However, we observed significant attenuation of PGE₂-induced prolongation of hyperalgesia in the group previously treated with PTX ($F_{2,12} = 169.04$, $***P < 0.0001$, when the vehicle and PTX group were compared; two-way repeated-measures analysis of variance followed by Bonferroni post hoc test), indicating that the α subunit plays a role in the induction of sumatriptan-induced priming. BL: baseline (N = 6 paws per group).

In the present experiments, we observed that intradermal injection of sumatriptan produces mechanical hyperalgesia at the injection site, as has been reported in patients being treated for migraine.^{17,18,68,85} Also, the frequent use of triptans can lead to transition to MOH or chronic migraine.^{9,10,27,28,38,41,68,77,85} We observed that sumatriptan produces a neuroplastic change in nociceptor function such that PGE₂-induced mechanical hyperalgesia is markedly prolonged, a characteristic feature of both type I^{4,29,33,50,57,69,73} and type II^{7,8} hyperalgesic priming. However, the mechanism underlying priming induced by sumatriptan resembled type I rather than type II priming. Thus, unlike type II priming, which develops within a matter of a few hours,^{7,8} that induced by sumatriptan required 3 days to develop, characteristic of type I priming.^{4,12} A second difference was that, unlike type II priming, in which the prolongation of PGE₂ hyperalgesia is PKA dependent, that induced by sumatriptan was PKC ϵ dependent, another characteristic feature of type I priming.^{4,70} Furthermore, characteristic of type I,³⁰ but not type II priming,^{7,8} that induced by sumatriptan was reversed by administration of a protein translation inhibitor to the peripheral terminal of the primed nociceptor. Moreover, the ability of PTX to inhibit the induction of sumatriptan-induced priming is also characteristic of type I priming^{33,52,57} and type II priming induced by CPA,⁸ but not type II priming induced by DAMGO.⁷ In addition, sumatriptan is unable to produce priming in rats in which IB4-positive (nonpeptidergic), but not IB4-negative (peptidergic), nociceptors have been destroyed, a further feature of type I²⁹

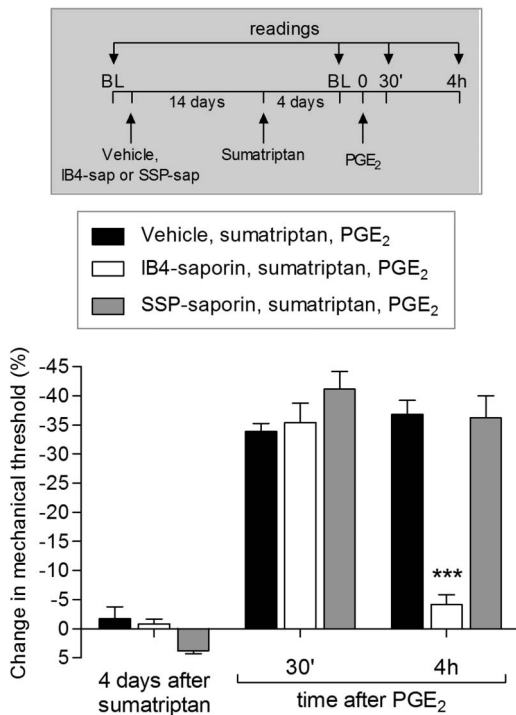


Figure 7. Type I priming induced by sumatriptan is dependent on isolectin B4 (IB4)-positive neurons. Male rats were treated with vehicle (5 μ L, black bars), IB4-saporin (3.2 μ g/20 μ L; white bars), or substance P-saporin (SSP-saporin) (100 ng/20 μ L; gray bars) by intrathecal injection. Fourteen days later, sumatriptan (10 ng) was injected on the dorsum of the hind paw. Four days later, when mechanical thresholds were not different from presumatriptan baseline (BL) ($t_5 = 1.663$; $P = 0.2010$, for the vehicle group; $t_5 = 1.667$; $P = 0.1942$, for the IB4-saporin group; $t_5 = 0.6547$; $P = 0.5799$, for the SSP-saporin group; paired Student t test), prostaglandin E₂ (PGE₂) (100 ng) was injected intradermally at the same site on the dorsum of the hind paw, and the mechanical hyperalgesia evaluated 30 minutes and 4 hours later. Two-way repeated-measures analysis of variance (ANOVA) followed by Bonferroni post hoc test showed PGE₂-induced hyperalgesia at 30 minutes in all groups, which was still present at the fourth hour, in vehicle (black bars) and SSP-saporin (gray bars) treated groups, but not in IB4-saporin (white bars) treated group, which at the fourth hour, the PGE₂-induced hyperalgesia was significantly blocked ($F_{1,15} = 26.95$, $***P = 0.0006$, when vehicle-treated groups are compared at the fourth hour with IB4-saporin-treated group; two-way repeated-measures ANOVA followed by Bonferroni post hoc test), indicating that the prolonged hyperalgesia induced by PGE₂ observed in the priming induced by sumatriptan occurs in IB4-positive neurons (N = 6 paws per group).

but not type II priming.^{7,8} Finally, unlike the type II priming induced by MOR or A1-adenosine receptor agonists,^{7,8} which occurs in female and also in male rats, sumatriptan induced priming only in males. Thus, we conclude that although the triptans act at GPCRs, which are involved in pain chronification as well as analgesia, when tested in a preclinical model, unlike other GPCR agonists, sumatriptan induces type I priming. However, the downstream signaling pathway through which an agonist at a GPCR induces type I priming remains to be established. In **Fig. 9**, the signaling pathways that participate in sumatriptan-induced type I hyperalgesic priming are illustrated.

Since the triptans act at two serotonin receptors, 5-HT_{1B} and 5-HT_{1D}, both of which are GPCRs, we evaluated the role that each subtype of receptor plays in the induction of hyperalgesic priming. We observed that while alone the antagonists of 5-HT_{1B} and 5-HT_{1D} receptor partially attenuate the prolongation of PGE₂ hyperalgesia, their coadministration completely prevented sumatriptan-induced prolongation of PGE₂ hyperalgesia. Furthermore, when agonists for

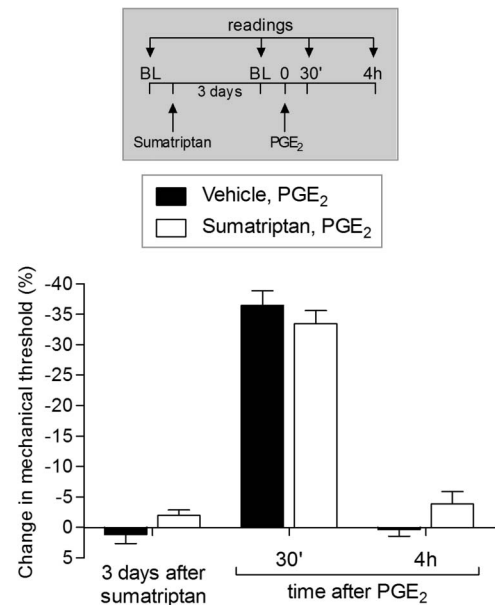


Figure 8. Sumatriptan did not induce prolongation of prostaglandin E₂ (PGE₂) hyperalgesia in female rats. Female rats received intradermal injection of vehicle (black bars) or sumatriptan (10 ng, white bars) on the dorsum of the hind paw. Three days later, when the mechanical thresholds were not different from prevehicle or presumatriptan baseline (BL) levels ($t_5 = 0.7559$; $P = 0.4838$, for the vehicle group; $t_5 = 2.150$; $P = 0.0842$, for the sumatriptan group, paired Student t test), PGE₂ (100 ng) was injected at the same site, and the mechanical hyperalgesia was evaluated 30 minutes and 4 hours later. Two-way analysis of variance followed by Bonferroni post hoc test showed that PGE₂ induced significant hyperalgesia at 30 minutes in both groups, which was not present at the fourth hour after its injection ($F_{1,15} = 0.83$; $P = 0.3779$, when compared both groups) (N = 6 paws per group).

each of these two serotonin receptors were injected, alone, each induced prolongation of PGE₂-induced hyperalgesia.

Why agonists at 5-HT_{1B} and 5-HT_{1D} induce type I priming while agonists at other GPCRs, namely, mu-opioid and A1-adenosine,

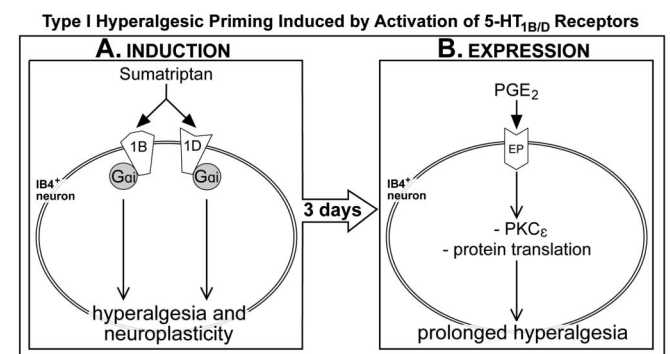


Figure 9. Schematic representation of the signaling pathways involved in sumatriptan-induced type I hyperalgesic priming. As shown in "A," the administration of sumatriptan (a 5-HT_{1B/D} receptor agonist), applied at the terminal of the IB4-positive nociceptor, triggers the events that will lead to mechanical hyperalgesia and the development of type I hyperalgesic priming. Activation of 5-HT_{1B} and 5-HT_{1D} receptors by administration of sumatriptan and the following activation of G-protein α subunit (G α), ultimately producing neuroplastic changes that are expressed as prolongation of the PGE₂-induced hyperalgesia. (B) PGE₂-induced hyperalgesia, which is dependent only on PKA in the normal state,³⁴ in the primed state is prolonged because of activation of an additional pathway involving PKC ϵ and protein translation. Abbreviations: 1B, 5-HT_{1B} receptor subtype; 1D, 5-HT_{1D} receptor subtype; EP, prostaglandin E receptor; PKC ϵ , protein kinase C epsilon; PGE₂, prostaglandin-E₂.

induce type II priming remains to be explained. One possible way to address the underlying differences would be to determine whether repeated administration of agonists at μ or A1 receptors induces a state whereby triptan agonists will now produce prolonged hyperalgesia, or vice versa. In preliminary experiments, we observed that although the repeated administration of the A1-adenosine receptor agonist CPA induces a state whereby the μ -agonist DAMGO induces hyperalgesia, the repeated administration of the MOR agonist DAMGO did not induce a state whereby the CPA induced hyperalgesia (unpublished results). Given this initial complexity, even for receptors whose agonists both induce type II priming, these experiments are beyond the scope of the present analysis.

In conclusion, in a model of pain chronification, induced by agonists at the triptan receptors 5-HT_{1B} and 5-HT_{1D}, key to the treatment of migraine, we have demonstrated that a clinically used member of this class of agonists, sumatriptan, induces both mechanical hyperalgesia at the site of injection and type I hyperalgesic priming, in nociceptors innervating the cutaneous injection site. Although our studies were executed outside the trigeminal system, the site of migraine, the basic neurovascular unit at both spinal and trigeminal levels is innervated by nociceptors that contain 5-HT_{1B} and 5-HT_{1D}.^{13,15,46,61,71,72,94} Moreover, support for shared mechanisms in spinal and trigeminal distributions comes from both the presence of a migraine variant, abdominal migraine,²⁰ which has been reported to be treatable with triptans in some patients,⁵⁴ as well as the observation that migraineurs do have lowered threshold in extracranial sites.¹⁹

Conflict of interest statement

The authors have no conflicts of interest to declare.

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