

Antihyperalgesic Effect of a Recombinant Herpes Virus Encoding Antisense for Calcitonin Gene-related Peptide

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Background: Calcitonin gene-related peptide (CGRP) is contained in and released by small-diameter, nociceptive primary afferent sensory neurons. Upon spinal release, one of the effects of CGRP seems to be to sensitize dorsal horn neurons to subsequent input from nociceptive afferents and, consequently, to induce a behavioral hyperalgesia. Therefore, attenuating evoked release of CGRP from central terminals of nociceptors should have an antihyperalgesic effect.

Methods: The authors applied a recombinant herpes vector, encoding an antisense sequence to the whole CGRP gene, to the dorsal surface of the hind paw of mice to knock down expression of the peptide selectively in primary afferents innervating this tissue.

Results: Herpes virus-based vector encoding an antisense sequence for the whole CGRP clearly reduced CGRP immunoreactivity in the infected spinal dorsal horn levels as well as in cultured dorsal root ganglia neurons. Selective knockdown of CGRP in primary afferents significantly attenuated the thermal, C-fiber hyperalgesia normally observed after topical application of capsaicin. The effect of viral vector-mediated knockdown of CGRP was comparable to the effect of intrathecal application of the CGRP antagonist CGRP₈₋₃₇, but lasted for 14 weeks after one single application.

Conclusion: Viral vector-mediated knockdown of CGRP in primary afferent neurons provides a promising tool for treatment of chronic pain states as well as for studies investigating the pathophysiology underlying these conditions.

CALCITONIN gene-related peptide (CGRP), a 37-amino acid peptide, is a ubiquitous marker of primary afferent neurons, where it is found in the majority of dorsal root ganglion (DRG) cell bodies at most spinal cord levels, in both myelinated and unmyelinated axons.^{1,2} More specifically, CGRP can be found in approximately 50% and 35% of C and Aδ fibers, respectively.³ Its colocalization

with substance P (SP)^{4–6} and many other neurotransmitters, such as aspartate, glutamate, somatostatin, and galanin,^{2,5–9} and the high concentration of CGRP fiber terminals terminating in laminae I and II of the dorsal horn of the spinal cord^{10,11} are indicative of its role in the cascade of peptides that signal noxious stimulation.

Calcitonin gene-related peptide, as with other primary afferent neuropeptides (e.g., SP), is synthesized in the somata of nociceptive afferents within the dorsal root ganglia to be transported to the peripheral and central nerve endings, where it can be released upon robust activation of those afferents.^{1,2,7,12,13} When released from central terminals, both CGRP and SP produce hyperalgesia to noxious, mechanical, and thermal stimuli but by different mechanisms.^{2,7} CGRP, when intrathecally administered, does not cause aversive behavior as does SP, but enhances responses of secondary cells to nociceptive input, including the effect of intrathecal SP.^{7,14–16} This may be due to the inhibition of SP metabolism by CGRP.¹² In addition, when released peripherally, CGRP prolongs and enhances vasodilatation and extravasation initiated by inflammatory mediators such as histamine, prostaglandins (e.g., PGE₂), and cytokines.^{12,15} In each case, the intrathecal, systemic, or peripheral application of anti-CGRP antibodies counteracts these effects and normalizes the mechanical hyperalgesia of arthritic rats,¹⁷ indicating that suppression of its effects may have analgesic, or at least antihyperalgesic actions.

We have previously used recombinant herpes simplex, type 1 viruses, as vectors to latently infect and transduce DRGs *via* peripheral infection to alter the phenotypes of mature primary sensory neurons.^{18–21} The purpose of this study was to determine the effect of use herpes simplex vectors to knock down the expression of CGRP exclusively in primary afferents by the use of the herpes virus encoding an antisense sequence to the CGRP gene and to investigate the effects of such a knockdown on capsaicin-induced thermal hyperalgesia mediated by sensitization of C thermoreceptors.

Preliminary results of this study have been published as part of a review.²⁰

Materials and Methods

Animals

Adult male Swiss Webster mice (22–25 g; Charles River Laboratories, Wilmington, MA) were housed in a 12-h

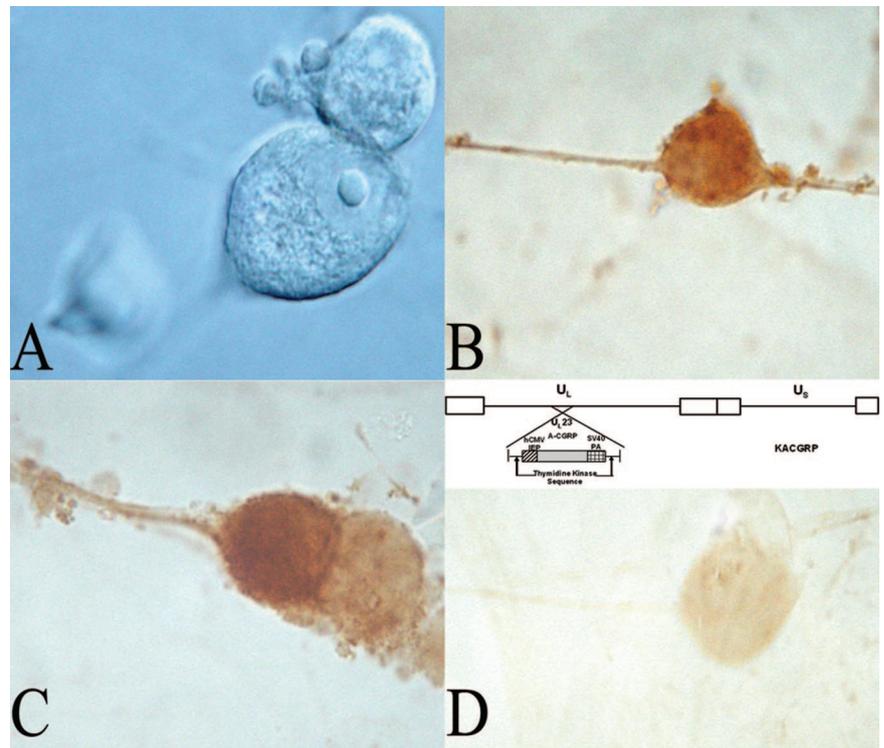
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Fig. 1. Photomicrographs of cultured mouse dorsal root ganglion (DRG) neurons. (A) Nomarski (1,000 \times) photo of DRG cells without calcitonin gene-related peptide (CGRP) primary antisera. (B) Strong CGRP immunoreactivity in a DRG neuron treated with capsaicin but not with virus (630 \times). (C) Strong CGRP immunoreactivity in DRG neurons treated with both capsaicin and control virus (KHZ) (630 \times). (D, bottom) Mild CGRP immunoreactivity in a DRG neuron treated with capsaicin and KACGRP (630 \times). (D, top) Diagram of recombinant herpes vector KACGRP. An antisense sequence to the gene for rat CGRP (A-CGRP) is inserted, under the control of a human cytomegaloviral immediate/early promoter/enhancer (hCMV IEP) sequence into the thymidine kinase (TK) sequence of the genome of an attenuated herpes simplex type 1 virus. Insertion into the TK sequence disables this gene and thus prevents replication in nondividing cells. A similar virus, KHZ, was constructed encoding for the bacterial reporter gene *lac-Z* and was used as a control. KACGRP = antisense CGRP viral vector; SV40 PA = simian virus 40 polyadenylation sequence; U_L = unique long sequence, U_S = unique short sequence.



light:12-h dark environment and provided food and water *ad libitum*. Effort was made to minimize discomfort and to reduce the number of animals used. All animal procedures were approved by University of Illinois at Chicago (Chicago, IL) and Stanford University (Stanford, CA) Institutional Animal Care and Use Committees.

Virus Construct

The herpes simplex virus vector was constructed as previously described, with modifications.^{18,20,21} In brief, a cassette containing the human cytomegalovirus immediate-early promoter/enhancer, SV40 intron, a nearly full-length complementary DNA for the rat CGRP precursor, and SV40 polyadenylation sequence was cloned from plasmid pCM-VrACGRP into pBluescript II SK(\pm) containing an inserted lox P site (fig. 1). This plasmid was reacted with Cre recombinase in the presence of ICP4⁻ viral DNA containing a lox P site in the thymidine kinase locus, as described. The virus designated SACGRP was isolated on a complementing cell line and was purified by three rounds of limiting dilution. Virus SACGRP was rescued by reintroduction of ICP4 DNA with selection of Vero cells, generating a recombinant vector designated KACGRP. Southern blotting confirmed correct insertion of the A-CGRP cassette. KACGRP-mediated expression of antisense CGRP was verified by infection of primary bovine adrenal chromaffin cells and BSC-40 cells followed by Western blotting with CGRP monoclonal antibody.

A similar constructed virus named KHZ encoding for the bacterial reporter gene *lac-Z* served as a control virus.

In Vitro Experiments

Cell Preparation and Assay. In four separate experiments, two mice each were killed during deep isoflurane anesthesia, and the DRGs L3–L6 were removed, collected, and digested in collagenase (2 mg/ml, type 1A; Sigma, St. Louis, MO) and dispase (1 mg/ml; Sigma). After 40 min, the ganglia were triturated and returned to the water bath for an additional 10 min. Enzymatic digestion was halted by the addition of cold Dulbecco's modified Eagle's medium (DMEM). Cells were centrifuged at 400 rpm for 10 min. The cell pellet was resuspended in 5 ml DMEM and passed through a sterile 20- μ m nylon mesh into a 50-ml conical tube. After centrifugation, cells were resuspended in 1–2 ml DMEM plus 10% fetal bovine serum. Cells were allowed to settle on poly-L-lysine-coated coverslips and placed in the incubator at 37°C. On the next day, 2 mM cytosine arabinoside was added to inhibit mitosis. Two days later, one half of the media was replaced with DMEM plus 10% fetal bovine serum. On the next day, cells were exposed to 5 μ M capsaicin dissolved in ethanol and diluted in DMEM plus 10% fetal bovine serum and placed in the incubator for 10 min. Cells were exposed to capsaicin to deplete intracellularly stored CGRP, thereby amplifying the signal for antisense-induced knockdown. Immediately after CGRP depletion, the media was changed such that either KACGRP or KHZ or vehicle was diluted in DMEM plus 10% fetal bovine serum to 1×10^6 pfu/ml and added to the cells. After waiting 2 days to allow for replenishment of CGRP stores, cells were fixed with 4% paraformaldehyde in phosphate-buffered saline (pH 7.4) on ice for 60 min.

Immunohistochemistry. To estimate infectivity of the viral vector used in this study, three wells of KHZ-infected cultures were stained for the presence of β -galactosidase, the protein product of the *lac-Z* gene inserted by KHZ. β -Galactosidase was localized after blocking in 10% normal donkey serum and overnight incubation in rabbit anti- β -galactosidase (1:2,000; Chemicon, Temecula, CA) followed by a biotinylated donkey anti-rabbit secondary antibody (1:200) for 60 min at room temperature. Streptavidin-conjugated horseradish peroxidase was used to amplify the signal. Visualization of β -galactosidase localization was performed by incubating the coverslips in 0.5 mg/ml 3,3'-diaminobenzidine in 0.1 M phosphate buffer, pH 7.4, for 20 min. Coverslips were washed extensively with 0.1 M phosphate buffer before dehydrating in a graded ethanol series and mounting in DPX (Sigma).

In vitro estimation of knockdown of CGRP by KACGRP was performed as above; however, rabbit anti-CGRP (1:2,000; Affiniti Research Products, Devon, United Kingdom) was used as the primary antibody.

Cellular analysis was performed by determining the percentage of diaminobenzidine positive intact neurons using a Leica DMRXA (Leica Microsystems GmbH, Wetzlar, Germany).

In Vivo Experiments

Drug Administration. Intrathecal administration of drugs was accomplished *via* lumbar puncture (L5) with a 1-ml syringe (Becton Dickinson, Franklin Lakes, NJ).¹⁸ Paw withdrawal latencies were recorded before intrathecal injection of drugs and at 0, 15, 30, 45, and 60 min after injection. Vehicle was comprised of preservative-free saline and India ink (10:1). Mice that did not show proper injection of drug, as indicated by the presence of India ink within the intrathecal space, were excluded from the study. CGRP (Sigma) was delivered intrathecally in 10 μ l vehicle at doses ranging from 0.1 to 10 nmol. The CGRP antagonist (10 nmol CGRP₈₋₃₇; Sigma) was administered intrathecally immediately after topical application of capsaicin. There is typically a several-minute delay between topical application of capsaicin and activation of nociceptors²²; therefore, the antagonist was administered at a time just before likely maximal CGRP release. Paw withdrawal latencies were recorded as described below.

Application of Virus. Mice were anesthetized with freshly prepared tribromoethanol (500 mg/kg). Calcium thioglycolate (Nair; Church & Dwight, Princeton, NJ) was applied liberally to the left hind paw. After 5 min, Nair was removed with a patch of sterile gauze. Another sterile patch of gauze was used to wash and dry the hind paw before the application of the virus. Five microliters (1×10^6 pfu/ μ l) of the herpes simplex type 1 vector, *i.e.*, KACGRP or KHZ, respectively, was applied and spread over the hind paw with a pipette tip.^{18,20,21} The

control virus was applied to the hind paws of control animals in an identical manner.

Behavioral testing was performed after topical application of capsaicin at 1.5, 4, 6, 8, 10, 14, and 17 weeks after application of KACGRP or KHZ, respectively, to determine the time course of antihyperalgesic effect after viral infection.

Behavioral Assay. Paw withdrawal responses to noxious radiant heat previously described for use in rats²²⁻²⁴ were adapted for use in mice.^{18,25} Mice were lightly anesthetized with pentobarbital (50 mg/kg intraperitoneal). Light anesthesia (*i.e.*, animals are crawling around, lifting their heads, and sniffing) has been shown to be useful when using the A δ /C test for measuring thermal hyperalgesia.^{18,25} In this test, the dorsal as opposed to the plantar surface of the hind paw is being stimulated, which makes it necessary to optimize animals' position. Light anesthesia does not affect nociceptive responses in this test^{18,22} and limits stress-induced analgesia as well as learning, both of which can be problems in behavioral nociceptive testing. Paw withdrawal latencies were recorded after thermal stimulation at two distinct heating rates, 0.9°C/s and 6.5°C/s, which selectively activate C and A δ thermoreceptors, respectively. We have previously demonstrated that withdrawal responses to these stimuli occur at average latencies of $13.4^\circ \pm 0.5^\circ$ and $2.7^\circ \pm 0.1^\circ$ C respectively, and surface skin temperatures of $47.2^\circ \pm 0.4^\circ$ and $51.7^\circ \pm 0.3^\circ$ C.²³ Cutoff latencies of 20 and 6 s, which we have shown produce peak surface temperatures of $48.7^\circ \pm 0.2^\circ$ and $62.9^\circ \pm 0.7^\circ$ C, respectively, were used to prevent tissue damage. Sensitization of C fibers was achieved *via* the topical application of 20 μ l capsaicin, 0.1%, dissolved in water:ethanol (50:50) applied to the viral vector-infected hind paw. Three baseline paw withdrawal latencies (PWLs) were measured before experimental manipulation (pre1, pre2, and pre3). Significant differences between groups ($n = 8-10$ /group) and across time were determined by analysis of variance for repeated measures followed by a *post hoc* Bonferroni analysis.

Measurement of CGRP Levels by Radioimmunoassay. Dorsal root ganglia from either side were separately analyzed for CGRP immunoreactivity by radioimmunoassay. Each DRG section was weighted for later standardization by weight. The DRGs were homogenized in 10 volumes by weight of artificial cerebrospinal fluid with 1 mg/ml complete peptidase inhibitor (Roche Bioscience, Palo Alto, CA) and centrifuged, and the supernatant was lyophilized before reconstitution for radioimmunoassay. CGRP levels were assayed using a radioimmunoassay kit (Peninsula Laboratories, San Carlos, CA) and analyzed using a Beckman gamma counter. CGRP levels were extrapolated from a standard curve. Significant differences between KACGRP-infected animals and controls were determined by the Student *t* test.

Immunohistochemistry. Deeply anesthetized mice (supplementary intraperitoneal pentobarbital) were perfused with 4% paraformaldehyde in 0.1 M phosphate buffer, pH 7.4. Spinal cords were removed and postfixed overnight at 4°C in 4% paraformaldehyde. After washing, tissue was cryoprotected in 30% sucrose before sectioning at 40 μ m and processed as free-floating sections. Ten sections were taken per segment and animal. Each group consisted of five mice. Nonspecific binding sites were blocked by incubating in 10% normal donkey serum in 0.1 M Tris-buffered saline, pH 7.4 with 1% bovine serum albumin. Without washing, sections were incubated overnight at 4°C with rabbit anti-CGRP (1:2,000; Peninsula Laboratories) diluted in 0.1 M Tris-buffered saline, pH 7.4 with 1% bovine serum albumin plus 2% normal donkey serum. After washing in 0.1 M Tris-buffered saline, pH 7.4, the tissue was incubated in donkey anti-rabbit immunoglobulin G (1:200; Amersham, Pittsburgh, PA) before transferring to streptavidin-horseradish peroxidase (1:100; Amersham). Localization was visualized with 0.001% hydrogen peroxide in 0.02 M aminodiethylcarbazol dissolved in 0.2 M sodium acetate, pH 5.2.

Image Analysis. Sections were collected on Superfrost Plus slides and observed using a Leica DMXA microscope (Leica Microsystems GmbH) at a magnification of 40 \times . Briefly, images of each slice were captured with a Sony F-707 digital camera (Sony, New York, NY) and imported into Adobe Photoshop (Adobe Systems Incorporated, San Jose, CA). The dorsal horns of both naive and antisense CGRP-infected mice were analyzed for optical density of standardized areas of interest. Each region of interest (laminae I and II) from superficial dorsal horns ipsilateral and contralateral to virus application was measured for area and mean optical density (in gray pixel units) using Image J version 1.26 (National Institutes of Health, Bethesda, MD).¹⁸ Slides were coded so that the evaluator was blinded to condition. Data from cord levels within each respective group (naive *vs.* infected) were then combined, and the products were analyzed for statistical significance using analysis of variance by a *post hoc* Bonferroni analysis.

Results

In Vitro Experiments

The average transduction rate of *lac-Z* by KHZ as indicated by staining for the presence of β -galactosidase was 63% (data not shown). Knockdown of CGRP was assessed by comparing the number of neurons that demonstrated dense CGRP immunoreactivity in KACGRP-infected, KHZ-infected, and uninfected cultured DRG neurons after exposure to capsaicin. The number of densely labeled CGRP-immunoreactive cells was significantly lower in KACGRP when compared with KHZ-infected or uninfected neurons (table 1 and fig. 1). The percentage of cells with dense staining for CGRP after

Table 1. Immunoreactivity in Cultured DRG Neurons

	No Primary Antibody	Vehicle	KHZ Virus	KACGRP Virus
Total cells, n	125 \pm 23	237 \pm 44	136 \pm 18	124 \pm 27
% Dense staining	0	84.3 \pm 11.2	83.1 \pm 19.4	13.7* \pm 9.2

Introduction of KACGRP virus but not control (KHZ or vehicle) decreased the percentage of small (< 20 μ m) cultured dorsal root ganglion (DRG) neurons with dense staining for calcitonin gene-related peptide in capsaicin-treated cultures (data presented as mean \pm SEM).

* Significant difference compared with KHZ virus ($P < 0.05$, *t* test).

KACGRP virus = calcitonin gene-related peptide antisense virus; KHZ virus = control virus.

infection with KHZ was not significantly different from uninfected cells.

In Vivo Experiments

Effects of Intrathecal CGRP on Paw Withdrawal Latencies. The effects of intrathecal injection of CGRP on PWL were examined for both A δ and C fiber-selective heating rates. Figure 2 shows the percent change from baseline PWL for A δ and C thermonociception after application of different doses of CGRP. PWLs for the low, *i.e.*, C fiber-selective, heating rate were significantly shorter after administration of 1, 5, and 10 nmol CGRP. PWLs for the high, *i.e.*, A δ fiber-selective, heating rate were not significantly changed by intrathecal CGRP, except at a dose of 5 nmol, and then only minimally (but significantly). The intrathecal administration of vehicle had no effect on PWL (data not shown).

Effects of Intrathecal CGRP₈₋₃₇ on Paw Withdrawal Latencies. As previously reported,^{21,22,24} topical application of capsaicin significantly decreased latencies for C fiber-mediated (fig. 3) but not A δ -mediated paw withdrawal responses (data not shown). This effect lasted for at least 60 min and was unaffected by intrathecal application of vehicle. Conversely, intrathecal application of the CGRP antagonist CGRP₈₋₃₇ significantly

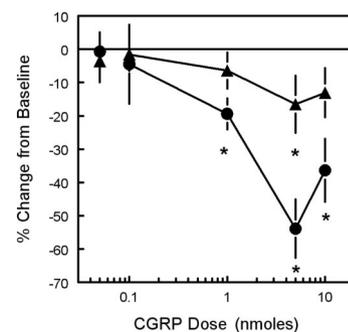


Fig. 2. Dose-dependent effect of intrathecal calcitonin gene-related peptide (CGRP) on nociceptive responses. **Filled triangles** represent the percent decrease in latency of paw withdrawal responses to A δ nociceptor activation. **Filled circles** represent the decrease in C fiber-mediated responses. * Significant decreases in response latency as compared with baseline, indicating hyperalgesia ($P < 0.05$, analysis of variance, $n = 8$ /group).

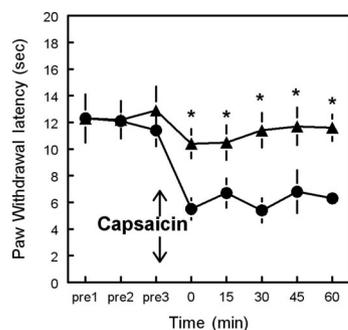


Fig. 3. Antihyperalgesic effect of intrathecal injection of 10 nmol of the calcitonin gene-related peptide antagonist CGRP₈₋₃₇. Topical application of capsaicin produced a robust decrease in the latency of paw withdrawals evoked by C fiber stimulation that was reversed by intrathecal injection of the antagonist (filled triangles) but not by vehicle (filled circles). * Significant ($P < 0.05$, analysis of variance, $n = 10/\text{group}$) attenuation of the hyperalgesic effect of capsaicin application. Data are presented as mean \pm SEM. Pre1, pre2, and pre3 represent baseline paw withdrawal latencies that were measured before experimental manipulation.

attenuated capsaicin-evoked hyperalgesia for C fiber-mediated responses. Application of the antagonist in the absence of capsaicin hyperalgesia had no effect (data not shown).

CGRP Levels in DRGs after Viral Infection as Measured by Radioimmunoassay. Calcitonin gene-related peptide levels in DRGs L1–S1 6 weeks after unilateral KACGRP infection of the hind paw were significantly lower compared with contralateral control DRGs (fig. 4), indicating a sufficient knockdown of CGRP after viral infection.

CGRP Immunoreactivity in the Dorsal Horn of the Spinal Cord after Viral Infection. To investigate the effects of topical application of the KACGRP virus to one hind paw of rats on CGRP immunoreactivity in superficial layers (laminae I and II) of spinal dorsal horns, we collected spinal cords of animals 6 weeks after viral infection (fig. 5A). The reduction of CGRP immunoreactivity was only significant at the levels of L4–L5 (fig. 5B),

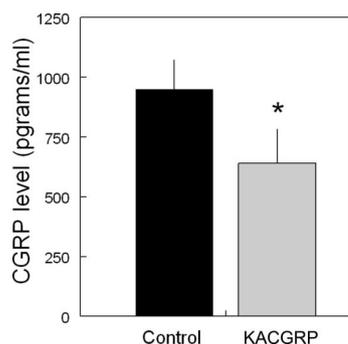


Fig. 4. Calcitonin gene-related peptide (CGRP) levels in dorsal root ganglia as measured by radioimmunoassay were significantly ($P < 0.05$, t test, as indicated by the asterisk) lower 6 weeks after unilateral infection with the KACGRP vector compared with the control dorsal root ganglia contralateral to the viral infection. Data are presented as mean \pm SEM. KACGRP = antisense CGRP viral vector.

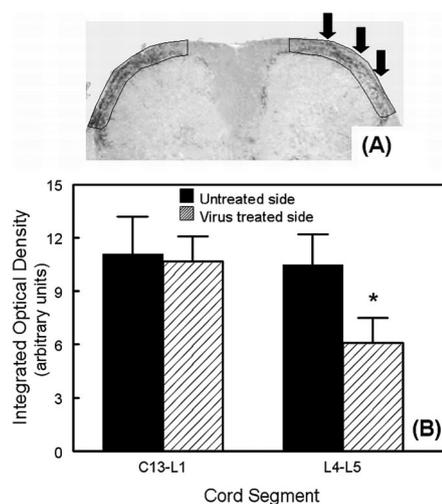


Fig. 5. (A) Calcitonin gene-related peptide (CGRP) immunohistochemical labeling in mouse dorsal horn after application of KACGRP to one hind paw. Low magnification (5 \times) photomicrograph of CGRP immunoreactivity demonstrates a decrease in labeling in the primary afferents terminating in the dorsal horn ipsilateral to vector application (black arrows). Black lines represent the selected regions of interest. (B) Semiquantitative evaluation of CGRP immunoreactivity in the superficial dorsal horn of mice 6 weeks after treatment of one paw with KACGRP. KACGRP treatment significantly ($P < 0.05$, analysis of variance, as indicated by the asterisk) but unilaterally decreased labeling for CGRP (measured in optical density) in the lower lumbar spinal dorsal horn (L4–L5) but not in lower cervical/upper lumbar segments (C13–L1). Results were averaged across five animals per group, 10 sections per segment. KACGRP = antisense CGRP viral vector.

which correspond to the levels that innervate the infected dorsal hind paw.²⁶ No significant decrease in CGRP immunoreactivity was seen at the C13–L1 level. Application of KHZ had no effect on CGRP immunoreactivity at either of the levels examined (data not shown).

Effects of KACGRP on Capsaicin-induced Hyper-sensitivity. After application of KACGRP or KHZ, baseline latencies for both A δ (data not shown) and C fibers remained unchanged (fig. 6). Topical application of capsaicin produced a profound C fiber-selective thermal hyperalgesia for at least 60 min in mice that were infected with the control virus KHZ. This hyperalgesia was not seen in mice that had been infected with KACGRP. The antihyperalgesic effect of KACGRP lasted for at least 60 min at the 10 weeks post-viral infection time point (fig. 6) and was significant from 1.5 to 14 weeks after infection, but was no longer observed at the 17 weeks time point (fig. 7). Four weeks after infection with KACGRP, there seemed to be an analgesic effect rather than an antihyperalgesic effect, *i.e.*, PWLs longer than baseline PWLs.

Discussion

This study sought to investigate the effects of intrathecal administration of CGRP and CGRP₈₋₃₇—a CGRP an-

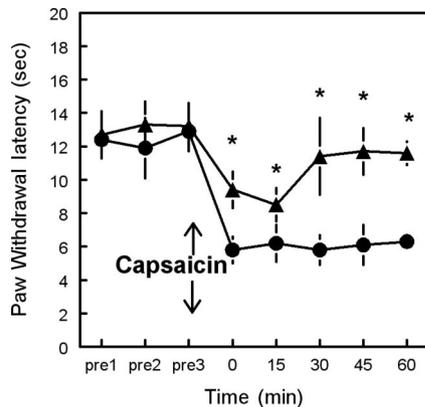


Fig. 6. Antihyperalgesic effects on C fibers of recombinant antisense calcitonin gene-related peptide viral vector: 10-week prior application to the hind paw of KACGRP (filled triangles) but not KHZ (filled circles) attenuated the C-fiber thermal hyperalgesic effect of capsaicin application. * Significant ($P < 0.05$, analysis of variance, $n = 10/\text{group}$) differences between control (KHZ) animal responses versus those of KACGRP animals. Data are presented as mean \pm SEM. Pre1, pre2, and pre3 represent baseline paw withdrawal latencies that were measured before experimental manipulation. KACGRP = antisense calcitonin gene-related peptide viral vector.

tagonist—and the effects of the selective knockdown of CGRP using herpes simplex-based vectors in primary afferents on PWL to noxious skin heating. Of particular interest in the behavioral assay were the differential effects on A δ and C thermonocceptors, respectively.

The extent of CGRP knockdown after infection of cultured DRG neurons with KACGRP was approximately 80% compared with uninfected or KHZ infected neurons. These findings are comparable to those of Cheli *et al.*,²⁷ who recently found a 74% decrease of the *N*-methyl-D-aspartate receptor NR1 subunit after infection of cultured neurons with their antisense herpes simplex-based vector *in vitro*. CGRP levels in the lumbar DRGs as measured by radioimmunoassay were signifi-

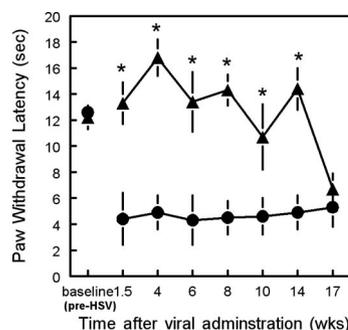


Fig. 7. Time course of the antihyperalgesic effect of KACGRP. When measured 30 min after topical capsaicin application, response latencies of KACGRP-treated mice (filled triangles) were significantly ($P < 0.05$, analysis of variance, as indicated by the asterisks, $n = 10/\text{group}$) longer than those of KHZ-treated animals (filled circles) up to 14 weeks after application. Data are presented as mean \pm SEM. KACGRP = antisense calcitonin gene-related peptide viral vector; KHZ = control virus; pre-HSV = before application of herpes vectors, *i.e.*, KACGRP or KHZ, respectively.

cantly lower compared with controls, indicating a satisfactory *in vivo* transfection rate.

Intrathecal application of CGRP led to a dose-dependent decrease in PWL to C fiber-selective noxious skin heating. The findings are consistent with the results of groups that found development of mechanical hyperalgesia after intrathecal application of CGRP.^{28,29} It should be mentioned that there is also one study that did not find nociceptive behavior after intrathecal administration of CGRP.³⁰ However, doses used in this study were lower (10–100 pmol CGRP) as compared with the doses used in our study (0.1–10 nmol). Other laboratories reported reversal of capsaicin-induced hyperalgesia as assessed by paw pressure latency, paw immersion latency, and hot-plate latency by intraplantar injections of the CGRP antagonist CGRP₈₋₃₇³¹ and antinociceptive effects of an antiserum against CGRP on thermal and mechanical noxious stimuli, when administered intrathecally,¹⁷ indicating that several sites of action might exist for CGRP-induced hypersensitivity.

To our knowledge, there is no study investigating the differential behavioral effects of CGRP on C and A δ thermonocceptors. The fact that the majority of neurons displaying CGRP immunoreactivity had a conduction velocity below 2.5 m/s³² indicates that at least the bulk of releasable CGRP is stored in C fibers. Furthermore, it has been shown that neonatal capsaicin treatment which destroys a large portion of C fibers significantly reduces CGRP levels in the dorsal horn of the spinal cord.³³ These observations are consistent with our findings of decreased PWLs for C-fiber thermonociception, whereas PWLs for A δ fiber-selective heating were unchanged after intrathecal CGRP injection.

Selective knockdown of CGRP in primary afferents using a viral vector-mediated antisense technique significantly attenuated the thermal, C-fiber hyperalgesia normally observed after topical application of capsaicin. This antihyperalgesic effect was comparable to the effect of intrathecal application of the CGRP antagonist CGRP₈₋₃₇ but lasted for 14 weeks after one single application. There is a slight discrepancy in the time course of PWLs after application of capsaicin to the skin after viral infection (fig. 6) when comparing the previously published preliminary data²⁰ and the results presented here, which can be explained by the larger number of animals per group used in this study.

Studies with α CGRP-deficient mice found no significantly different nociceptive behavior compared with wild-type mice as tested by the tail-flick and hot-plate test.³⁴ However, they did show an attenuated response to chemical pain and inflammation.³⁵ Another study with mice deficient in the α CGRP gene found normal responses to noxious radiant heat stimuli; however, in contrast to wild-type mice, animals did not develop signs of secondary hyperalgesia in an inflammatory pain model.³⁶ These data may reflect some inherent differences

between the knockout approach and the selective knockdown of peptides in adults using herpes simplex virus-directed transduction. Compensatory changes in the expression of other transmitters are more likely to occur in knockout mice and could explain discrepancies to studies with (vector-mediated) knockdown in adult animals. Such compensatory changes are known to occur in knockout animals. For example, a study with *sns*-null mutant mice, *i.e.*, mice lacking the $\text{Na}_v1.8$ channel, found a significant compensatory up-regulation of tetrodotoxin-sensitive sodium channels by 100%.³⁷ In addition, CGRP, when administered into the periaqueductal gray of rats, produced antinociceptive effects that were counteracted by application of a CGRP antagonist.³⁸ These central anti- and peripheral pronociceptive effects of CGRP could compensate each other (in part) in CGRP-deficient mice. Therefore the method used in this study, *i.e.*, the selective knockdown of CGRP solely in primary afferents of a specific anatomical region, in adults, has unique utility in determining the function of CGRP in primary afferent nociceptors.

Chronic administration of opioids results in a decrease of, or tolerance to, its pharmacologic effects, such as antinociception. CGRP has been shown to decrease the analgesia produced by μ or δ agonists.³⁹ On the other hand, opioids have been shown to inhibit the release of CGRP.⁴⁰ Simultaneous administration of morphine and the CGRP antagonist CGRP₈₋₃₇ prevented the development of tolerance to the antinociceptive effects of morphine in experimental pain models.⁴¹ These data indicate that treatment with a CGRP antagonist could be a useful adjuvant for treatment of pain, more specifically for the prevention or attenuation of tolerance to the antinociceptive effects of morphine. The long-lasting effect after single application and the transdermal bioavailability of the viral vector encoding for CGRP antisense used in this study make it a valuable tool for further studies.

Pohl and Braz⁴² used an antisense CGRP viral vector to reduce the enhanced synthesis of CGRP induced in DRG neurons by peripheral injection of complete Freund adjuvant. They found a 50% decrease in CGRP-like material in lumbar DRGs in rats that were infected with the vector encoding for antisense CGRP as compared with controls. In addition, the concomitant inflammatory paw edema was less in animals infected with the antisense CGRP virus. The effects of reduced CGRP up-regulation and reduced paw edema were only significant up to 12 days or investigated for 16 days after induction of inflammation, respectively. However, these authors used a different promoter (modified herpes simplex virus latency promoter) in their viral vector. Unfortunately, this study did not assess changes in behavior to noxious stimuli.

Monkeys treated with a similarly constructed enkephalin-encoding virus as used in this study demonstrated

behavioral antihyperalgesic effects that lasted for at least 20 weeks in a thermal/capsaicin model.⁴³ Therefore, we would expect that the antisense CGRP vector used in this study would also function in primates and thus may be applicable to human pain conditions. Using replication-deficient herpes vectors to alter the phenotype of primary afferent nociceptors is also a powerful tool to explore mechanisms of pain and hyperalgesia.

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