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Painful Pathways Induced by TLR Stimulation of Dorsal Root Ganglion Neurons

Jia Qi,* Kristzina Buzas,*† Huiting Fan,* Jeffrey I. Cohen,‡ Kening Wang,‡ Erik Mont,‡ Dennis Klinman,§ Joost J. Oppenheim,* and O. M. Zack Howard*  

We hypothesize that innate immune signals from infectious organisms and/or injured tissues may activate peripheral neuronal pain signals. In this study, we demonstrated that TLRs 3, 7, and 9 are expressed by human dorsal root ganglion neurons (DRG�) and in cultures of primary mouse DRG�. Stimulation of murine DRG� with TLR ligands induced expression and production of proinflammatory chemokines and cytokines CCL5 (RANTES), CXCL10 (IP-10), IL-1α, IL-1β, and PGE₂, which have previously been shown to augment pain. Further, TLR ligands upregulated the expression of a nociceptive receptor, transient receptor potential vanillioid type 1 (TRPV1), and enhanced calcium flux by TRPV1-expressing DRG�. Using a tumor-induced temperature sensivity model, we showed that in vivo administration of a TLR9 antagonist, known as a suppressive oligodeoxynucleotide, blocked tumor-induced temperature sensitivity. Taken together, these data indicate that stimulation of peripheral neurons by TLR ligands can induce nerve pain. The Journal of Immunology, 2011, 186: 6417–6426.

Toll-like receptors play a fundamental and essential role in host defense during pathogen infection by regulating and linking innate and adaptative immune responses (1, 2). The 12 mammalian TLRs belong to a family of receptors that recognize pathogen-associated molecular patterns and can be divided into those that are expressed in the cell membrane and those located in endosomes. The ones located in endosomes, TLR3, TLR7/8, and TLR9, are activated by double-stranded and single-stranded nucleotides of viral or cellular origin. Innate immune cells sense viral infection by detecting viral proteins and/or nucleic acids. TLR3 is known to be a major mediator of the cellular response to viral infection because it responds to dsRNA, a common by-product of viral replication (3), whereas TLR7 and TLR9 are activated by ssRNA and cytosine-guanosine (CpG) DNA, respectively.

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Abbreviations used in this article: Ana, anandamide; CAP, capsaicin; DRG, dorsal root ganglion; DRGN, dorsal root ganglion neuron; NGS, normal goat serum; ODN, oligodeoxynucleotide; poly:IC, polyinosinic-polycytidylic acid; Sup ODN, suppressive oligodeoxynucleotide; TRPV1, transient receptor potential vanillioid type 1.
Thus, some TLRs provide a key link between the innate immune system and the nervous system (14–16). This led us to hypothesize that TLR ligands generated by viral infections or cell death may induce painful signals in the peripheral nervous system by stimulating peripheral sensory neurons exemplified by dorsal root ganglion neurons (DRGns). We therefore investigated whether DRGns express TLRs and whether the TLRs participate in the pain signals when stimulated by TLR 3, 7, or 9 ligands.

In the current study, we demonstrate that both human and mouse DRGns express TLR3/7/9 and that stimulating mouse DRGns with TLR3/7/9 ligands increased TLR3/7/9 expression. Murine DRGns stimulated with TLR ligands increase mRNA expression and protein production of many inflammatory cytokines and chemokines, which have previously been identified as mediators of pain hypersensitivity. Further, TLR ligands upregulated the expression of TRPV1, a nociceptive receptor, and also enhanced calcium (Ca²⁺) flux mediated by TRPV1. These results provide new insights into the role of TLRs in pain signaling by peripheral neurons.

Materials and Methods

Primary DRG culture

These studies were performed in compliance with the principles and procedures outlined in the National Research Council’s Guide for the Care and Use of Laboratory Animals and were approved by the National Cancer Institute-Frederick Animal Care and Use Committee under Animal Study Protocols 08-005 and 10-218. DRG cultures were prepared as described previously (17, 18) with modifications (19). A detailed description of the procedure for the removal of rat dorsal root ganglia (DRGs), used in this article for both mice and rats, can be found elsewhere (20) as can concerns about plating surface coatings (21). Briefly, DRGs were dissected from 13- to 14-day-old mouse embryos of NIH Swiss mice [NIH Swiss is N:NIH(S), which was derived from the N:G(PS) colony in 1936; C57BL/6N mice (NIC Animal Production Program 1999 restart), or MyD88 knockout mice (from Dr. S. Akira, Research Institute for Microbial Diseases, Osaka University, Osaka, Japan; further back-crossed to C57BL/6N by Dr. D. Klinman, National Cancer Institute), respectively. Trypsin-EDTA 0.05% (Life Technologies, Carlsbad, CA) was added to the ganglia and incubated at 37°C for 10 min. After centrifugation at 350 × g for 5 min, the cells were resuspended in DMEM (Mediatech, Herndon, VA) containing 57°C heat-inactivated 10% FBS (nucleate containing; HyClone, Thermo Scientific, Logan, UT), 4 mM t-glutamine (Quality Biological, Gaithersburg, MD), and penicillin–streptomycin 100 U/ml and 100 mg/ml, respectively; Quality Biological). The cells (7.5 × 10⁵) were then plated onto 4-well or 8-well chambered coverglass (Nunc, Rochester, NY) precoated with poly-l-lysine (Sigma-Aldrich, St. Louis, MO) and collagen type I (Inamed, Minneapolis, MN). The cultures were then incubated overnight at 37°C for 12 h. The following day, the cultures were then washed with PBS three times each for 5 min and mounted using prolong gold antifade reagent with DAPI (P36935; Invitrogen) and examined with a Zeiss LSM 510 laser-scanning microscope (Carl Zeiss MicroImaging, Thornwood, NY) equipped with argon (excitation 488 nm), DPSS (excitation 561 nm), and diode (excitation 405 nm) lasers. We used the following procedure to calculate the average intensity of TRPV1 in the neuron surface and dendrites before and after stimulation with TLR ligands: Otsu’s global thresholding algorithm (24) was used to identify the β-III tubulin in the red channel. The resulting binary mask of the red channel was then used to calculate the average intensity of TRPV1 in the neuron surface and dendrites (green channel). All image-processing steps were performed using a custom ImageJ (National Institutes of Health; http://rsb.info.nih.gov/ij/) script.

Western blot analysis

DRG cultures were lysed in ice-cold lysis buffer (62.5 mM Tris-HCl, pH 6.8, 2% w/v SDS, 10% glycerol, 50 mM DTT), briefly sonicated, and centrifuged at 17,000 × g at 4°C for 10 min. Total protein in the supernatant was determined using the BCA Protein assay kit (Pierce, Thermo Scientific, Logan, UT). As a positive control, spleen extract was treated as described above. Equal amounts of protein were subjected to electrophoresis on NuPAGE Novex Bis-Tris (Invitrogen, Carlsbad, CA) in 4–12% gradient gels in MOPS buffer and then transferred to polyvinylidene fluoride membranes (Millipore, Billerica, MA). The membranes were blocked in nonfat dry milk (0.5% BSA) in TBS (0.1 mg/ml heparin sulfate) supplemented with 0.1% Tween 20, pH 7.4, with 5% nonfat dry milk at room temperature for 1 h. The membranes were then incubated with rabbit polyclonal Ab against TLR3, TLR7, and TLR9 (1:1000; Prosci), rabbit anti-neuron–specific β-III tubulin (1:2000; R&D Systems) was used as the control band (GAPDH). The signal for each lane was calculated by summing the immunoreactive bands were digitized, and the densitometry was performed on NuPAGE Novex Bis-Tris (Invitrogen, Carlsbad, CA) in 4–12% gradient gels in MOPS buffer and then transferred to polyvinylidene fluoride membranes (Millipore, Billerica, MA). The membranes were blocked in nonfat dry milk (0.5% BSA) in TBS (0.1 mg/ml heparin sulfate) supplemented with 0.1% Tween 20, pH 7.4, with 5% nonfat dry milk at room temperature for 1 h. The membranes were then incubated with rabbit polyclonal Ab against TLR3, TLR7, and TLR9 (1:1000; Prosci), rabbit anti-TRPV1 (1:1000; Novus Biologicals), and rabbit anti-GAPDH (1:1000, cat. no. 2118; Cell Signaling Technology, Danvers, MA) overnight at 4°C. The blots were washed three times in TBST and incubated with HRP–labeled anti-rabbit and anti-mouse (1:1000, Cell Signaling Technology) for 1 h at room temperature. Blots were then visualized with ECL reagent (GE Healthcare, Pittsburgh, PA).

To quantify Western blot data, developed films were scanned, the immunoreactive bands were digitized, and the densitometry was performed using a custom ImageJ (National Institutes of Health; http://rsb.info.nih.gov/ij/) script. The signal for each lane was calculated by summing the area × intensity of immunoreactivity (gray level of immunoreactive background level) of TLR3/7/9 and TRPV1 and normalized with internal control bands (GAPDH). The results, which were presented as mean ± SEM, were expressed as percentages of levels in control group (100%) and statistically analyzed with Student t test for two-group comparisons. The level of significance was taken as p < 0.05. All experiments were performed at least three times.

PGEl detection

Supernatants from DRG cultures, which were pretreated with TLR ligands, poly:IC, gardiquimod, ODN 1826, or ODN 2088 (InvivoGen, San Diego, CA) were collected, respectively, and PGE2 was detected with PGE2 enzyme immunoassay (Cayman Chemical, Ann Arbor, MI) as indicated by the manufacturer.

Immunoochemistry

Immunoochemical analysis was performed on primary cultured embryonic murine DRGns and adult human DRG sections. Human ganglia were collected at autopsy less than 24 h after death, frozen on dry ice, and stored at −80°C before cryostat sections were obtained. The Office of Human Subjects Research at the National Institutes of Health deemed this research exempt. Cultured DRGns and human DRG cryostat sections were fixed with 4% paraformaldehyde for 10 min, washed with PBS three times each for 5 min, permeabilized with 0.1% Triton X-100 in PBS containing 1% normal goat serum (NGS) (Sigma-Aldrich) for 10 min, and washed with PBS three times each for 5 min. Samples were then blocked in 5% NGS at room temperature for 1 h. After blocking, the samples were then incubated with primary Abs, which included rabbit polyclonal Ab against TLR3 (cat. no. 3643), TLR7 (cat. no. 3269), TLR9 (cat. no. 3739) (1:200, respectively); Prosco, Poway, CA; these polyclonal Abs are mouse and human reactive). TRPV1 (cat. no. NB100-98866, 1:1000, human and mouse reactive; Novus Biologicals, Littleton, CO), and mouse monoclonal anti-neuron–specific β-III tubulin (1:200; R&D Systems) in 2% NGS overnight at 4°C. Rabbit IgG (1:200; R&D Systems) was used as the negative control for TLR ligand treatment. The samples were then washed with PBS three times each for 5 min and incubated with the appropriate secondary Abs including Alexa Fluor 546 goat anti-mouse (Invitrogen, Eugene, OR) or Alexa Fluor 488 goat anti-rabbit (Invitrogen) at a dilution of 1:1000 in 2% NGS in PBS for 1 h at room temperature. Samples were then washed with PBS three times each for 5 min and mounted using prolong gold antifade reagent with DAPI (P36935; Invitrogen) and examined with a Zeiss LSM 510 laser-scanning microscope (Carl Zeiss MicroImaging, Thornwood, NY) equipped with argon (excitation 488 nm), DPSS (excitation 561 nm), and diode (excitation 405 nm) lasers. We used the following procedure to calculate the average intensity of TRPV1 in the neuron surface and dendrites before and after stimulation with TLR ligands: Otsu’s global thresholding algorithm (24) was used to identify the β-III tubulin in the red channel. The resulting binary mask of the red channel was then used to calculate the average intensity of TRPV1 in the neuron surface and dendrites (green channel). All image-processing steps were performed using a custom ImageJ (National Institutes of Health; http://rsb.info.nih.gov/ij/) script.

PCR array

DRG cultures were treated with TLR ligands for 16 h. Total RNA was isolated from samples by RT² qPCR-Grade RNA isolation kit.
Ca²⁺ flux was mediated by TRPV1, we investigated the effects of SB-366791 (Biomol International, Plymouth Meeting, PA) or Ana (Sigma-Aldrich; final concentration 1.86, 5.57, 16.7, and 53.1 μM) or without the compound (control). The chambers were then incubated for 10 s. To confirm the Ca²⁺ flux was mediated by TRPV1, we investigated the effects of SB-366791 (Biomol International, Plymouth Meeting, PA), the selective TRPV1 antagonist (27). After being washed following dye fluo-3-AM loading, the neurons were incubated for 30 min at 25°C with SB-366791 (1 μM) or without the compound (control). The chambers were then placed onto the microscope plate before the addition of various activators of TRPV1. Images were analyzed for changes in intensity of Ca²⁺-mediated fluorescence using Fluoview version 1.7b software (Olympus, Center Valley, PA) and converted into Rainbow color (26).

Cytokine quantification

The expression of selected cytokines, chemokines, and their receptors in the supernatant of DRGN cultures was determined by multiplex array (Aushon Biosystems, Woburn, MA).

Ca²⁺ flux

DRGNs were maintained in 8-well chambered coverglass for 5 d. Time-lapse images (phase contrast) were captured with an Olympus Confocal Laser Scanning microscope, Fluoview FV1000 (Olympus, Center Valley, PA; equipped with a heated stage maintained at 25°C and with a constant CO₂ source [5%]). For Ca²⁺ imaging, the culture medium was removed, and DRGNs were washed with Krebs–Ringer solution (124 mM NaCl, 3 mM KCl, 2 mM CaCl₂, 2 mM MgCl₂, 1.3 mM NaH₂PO₄, 26 mM NaHCO₃, 10 mM dextrose, pH 7.4) (26). DRGNs in the coverglass chambers were loaded with fluo-3-AM (final concentration 5 μM in Krebs–Ringer solution) dissolved in 0.1% DMSO (Sigma-Aldrich) at 37°C for 30 min. DRGNs were then gently washed using Krebs–Ringer solution to remove free dye. Cultures were illuminated with 488-nm light from a multi Ar+HeNe (argon and HeNe) laser through an epifluorescence Olympus FV1000 IX81 inverted microscope with a 10×, 0.4 numerical aperture Olympus UPLAPO objective. Light passing through the aperture was filtered by a 505–600 nm band-pass filter (BAS605-600). The basal fluorescence level was recorded for 90 s just before the application of each reagent. Subsequently, 50 μl CAP (Sigma-Aldrich, Steinheim, Switzerland; final concentration 0.03, 0.1, 1, and 10 μM dissolved in 0.1% DMSO) or Ana (Sigma-Aldrich; final concentration 1.86, 5.57, 16.7, and 53.1 μM dissolved in 0.1% DMSO) were added for 10 s. To confirm the Ca²⁺ flux was mediated by TRPV1, we investigated the effects of SB-366791 (Biomol International, Plymouth Meeting, PA), the selective TRPV1 antagonist (27).

Tumor-induced temperature sensitivity

A tumor-induced temperature sensitivity model was adapted to our laboratory from earlier studies (28–30) to investigate whether TLR9 antagonist (Sup ODN) could decrease temperature sensitivity, which is mediated by TRPV1. This model is considered a neuropathic pain model because the tumor-bearing mice experience temperature hypersensitivity. The model was developed in conjunction with and approved by the National Cancer Institute-Frederick Animal Care and Use Committee (Animal Study Protocol 10-218). Two million S-180 cancer cells were inoculated into the muscular tissue of female Swiss Webster mice in the immediate vicinity of the sciatic nerve near the trochanter, immediately distal to where the posterior biceps semitendinosus branches off the common sciatic nerve. A negative control group was injected with PBS instead of tumor cells. Paw withdrawal latencies to radiant heat stimulation at 55°C were measured before any procedure and on days 2, 5, 7, 9, 11, 13, and 15 after tumor inoculation. Treatment groups consisted of ≥8 animals. Synthetic Sup ODNs were delivered i.p. in a dose range from 5 μg/mouse to 320 μg/mouse (22); the tumor control groups received PBS i.p.

Statistics

Statistical determination of PGE₂, and protein levels in supernatants of DRGN cultures were performed using Student t test and comparison with control (GraphPad Prism, version 4.0c; GraphPad, San Diego, CA). The p values <0.05 were considered statistically significant. Data for RNA array were analyzed by RT² Profiler PCR Array Data Analysis software (SABiosciences) and standard deviations calculated as recommended (31). Ca²⁺ responses in activated cells were individually identified and their correspondence with 488-nm emission measured using the Fluoview version 1.7b software. Data from activated cells on 8-well coverglass
chambers in three dependent experiments (a total of 30 cells) were analyzed in each condition (CAP, Ana only, or pretreated with TLR ligands), and Ca^{2+} responses (mean of the peak values) were plotted by using SigmaPlot 8.0 software (Fig. 8). The comparison of ligands-induced activation of TRPV1 between nontreated and TLR ligands-pretreated cells was carried out by two-way ANOVA with SPSS version 13.0. Linear regression and least squares comparison (GraphPad Prism, version 4.0c; GraphPad) were used to determine the slope and correlation within experimental groups.

**FIGURE 2.** Negative control staining for TLRs and TRPV1 in DRGNs (A), TRPV1 in human DRGN sections (B), and magnified images from human sections (C). Scale bars, 50 μm (A), 100 μm (B), and 10 μm (C), respectively.

**FIGURE 3.** Human DRG sections express TLR3, TLR7, and TLR9. Confocal images of DRG cryostat sections. Samples were stained with TLR3 (A), TLR7 (B), and TLR9 (C) (green), neuron-specific β-III tubulin (red), and DAPI (blue). Shown are separate monochrome images of the green, red, and blue fluorescence channel and merged color images from all channels. Scale bars, 50 μm.
treatment groups and one-way ANOVA with post tests used to determine the probability and dosing trend.

Results

TLR3/7/9 expressed by DRGNs

To show that DRGNs express TLR3/7/9, we established primary cultures from day 13 mouse embryos. In these cultures, >95% of the cells showed phenotypic properties of neurons (32, 33). Immunofluorescence staining on day 5 showed that TLR3, TLR7, or TLR9, which are pseudo-colored green in the micrographs, are expressed on neurons isolated from DRGs (Fig. 1A, 1B, 1C, respectively). Immunofluorescent controls are shown in Fig. 2A. We also found that TLR 3, 7, and 9 were expressed by neurons in adult human DRG tissue sections (Fig. 3A, 3B, 3C, respectively; negative controls shown in Fig. 2R, 2C). β-III tubulin, which is a neuron-specific marker, is pseudo-colored red in the micrographs, verifying that the cells expressing TLRs were neurons.

TLR ligands enhanced TLR3/7/9 expression by DRGNs

Based on our pilot studies (K. Buzas, J. Cohen, O.M.Z. Howard, and J.J. Oppeneheim, reported at the 2007 National Institutes of Health-Immunology Interest Group, Warrenton, VA), we deter-

FIGURE 4. TLR ligands induce corresponding receptor expression by DRGNs. Western blot showing TLR3, TLR7, and TLR9 expression by DRGNs after ligand stimulation are shown. A, Poly-IC (25 μg/ml) induced TLR3 protein expression in DRGNs. B, Gardiquimod (3 μg/ml) induced TLR7 protein expression in DRGNs. C, ODN 1826 (32 μg/ml) induced TLR9 expression in DRGNs. D, Densitometry from the blots. Cells were stimulated for 16 h then harvested, lysed, and the protein extracts were probed with anti-TLR3, anti-TLR7, and anti-TLR9 Ab. Control (Con) samples were cultured for 16 h without additional stimulation. Protein loading is reported using an anti-GPDH Ab. Spleen lysate was used as a positive control. One representative of more than three independent experiments is shown. Image densitometry was performed using ImageJ software. The densitometry results were determined for five sites within each band, presented as mean ± SEM, and are expressed as percentages of levels in control group (100%). GAPDH was used as internal control. Statistics analysis was performed using Student t test for two-group comparisons. **p < 0.01, ***p < 0.001 (compared with control).

FIGURE 5. TLR ligands induce PGE2 production by DRGNs. Supernatants of DRGN cultures were collected and PGE2 was detected using enzyme immunoassay after stimulation by poly-IC (25 μg/ml), gardiquimod (3 μg/ml), or ODN 1826 (32 μg/ml) for 16 h. Each bar represents the mean ± SEM (n = 10). A, PGE2 production by DRGNs from Swiss embryonic mice. B, PGE2 production by DRGNs from C57 and MyD88 knockout embryonic mice. Statistical analysis was performed using Student t test for two-group comparisons. **p < 0.01, ***p < 0.001 (compared with corresponding control), ##p < 0.01 (compared with corresponding C57 mice treated with gardiquimod and ODN 1826).
PGE2 is a central mediator of febrile response triggered by the inflammatory process, and intradermal PGE2 is hyperalgesic in the peripheral nervous system (34, 35). We determined the PGE2 levels in the supernatants of 5-d DRGN cultures after stimulation for 16 h. As shown in Fig. 5A, PGE2 concentration increased after stimulation by each of the TLR3/7/9 ligands compared with that of the control group (p < 0.005), which suggests that ligands for endosomal TLRs could induce DRGNs to produce this mediator of hyperalgesia and inflammation, namely PGE2. Moreover, we found that ODN 1826 (32 μg/ml) significantly increased PGE2 levels induced by ODN 1826 alone of maximum stimulation (p = 0.009). We also determined the PGE2 concentration in the supernatants of DRGN cultures of MyD88 knockout mice. As shown in Fig. 5B, gardiquimod and ODN 1826 failed to induce PGE2 production significantly in MyD88 knockout mice (p < 0.01), but as anticipated poly:IC did induce PGE2 in the knockout DRGN.

TLR ligands upregulated mRNA levels and protein expression of proinflammatory cytokines and chemokines by DRGNs

To confirm that ligands of endosomal TLRs induce a proinflammatory response by DRGNs, we performed real-time quantitative PCR (mouse Inflammatory Response and Autoimmunity PCR Array) to analyze mRNA levels in DRGNs after stimulation for 16 h with poly:IC, gardiquimod, or ODN 1826. As anticipated, TLR ligands dramatically increased CCL5, CXCL10, IL-1α, and IL-1β mRNA levels (Table I) (GSE27579, http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE27579). These factors were previously identified as important mediators of pain hypersensitivity (5–7, 36, 37). Furthermore, as shown in Table I, TLR3/7/9 ligands also increased IL-1α and IL-1β protein production. Moreover, poly:IC increased CXCL10 and CCL5 protein production, markedly. These data indicate that DRGNs respond to ligands of endosomal TLRs by producing high levels of proinflammatory mediators.

**TLR ligands increased TRPV1 expression and translocation by DRGNs**

The effect of TLR stimulation on TRPV1, the pain detector and integrator, was evaluated. As shown in Fig. 6. TLR ligands markedly increased TRPV1 (~100 kDa) expression by DRGNs. Moreover, TLR ligands enhanced translocation of TRPV1 proteins from cell bodies in DRGNs to sensory nerve endings (Fig. 7). The elevated TRPV1 expression and translocation suggested that the nociceptive neurons stimulated by TLR ligands are better able to

<table>
<thead>
<tr>
<th>Ligand</th>
<th>CCL5 (pg/ml)</th>
<th>CXCL10 (pg/ml)</th>
<th>IL-1α (pg/ml)</th>
<th>IL-1β (pg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly:IC (25 μg/ml)</td>
<td>289.9 ± 7.4*</td>
<td>73.8 ± 5.4*</td>
<td>9.7 ± 1.9*</td>
<td>10.9 ± 1.9*</td>
</tr>
<tr>
<td>Gardiquimod (3 μg/ml)</td>
<td>16.9 ± 1.56*</td>
<td>7.4 ± 0.35*</td>
<td>8.9 ± 0.69*</td>
<td>10.4 ± 1.7*</td>
</tr>
<tr>
<td>ODN 1826 (32 μg/ml)</td>
<td>9.1 ± 0.69*</td>
<td>7.6 ± 0.17*</td>
<td>6.4 ± 1.7*</td>
<td>6.6 ± 1.4*</td>
</tr>
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</table>

**Protein Concentration (pg/ml)**

Control: 16.6 ± 2.9
Poly:IC (25 μg/ml): 1,899.6 ± 762.6*
Gardiquimod (3 μg/ml): 76.8 ± 25.8
ODN 1826 (32 μg/ml): 25.0 ± 5.2

*Significantly different from control with p < 0.05. Data for RNA array were performed by Student t test.

**FIGURE 6.** TRPV1 expression is increased on DRGNs stimulated with ligands for endosomal TLRs. **A**, TRPV1 expression by DRGNs was detected by Western blot after stimulation by poly:IC (25 μg/ml), gardiquimod (3 μg/ml), or ODN 1826 (32 μg/ml) for 16 h. **B**, Densitometry from the blots (percentage of control). Image densitometry was performed using ImageJ software. GAPDH was applied as internal control. One representative of more than three independent experiments is shown. *****p < 0.001 (compared with control).
respond to pain stimuli. We next evaluated an in vitro correlate for pain sensation, calcium flux.

**TLR ligands enhanced Ca²⁺ influx induced by CAP and Ana**

For studies of Ca²⁺ influx, neurons were maintained in culture for 5 d and only small to medium-sized neurons were studied. Murine DRGNs responded with a persistent and concentration-dependent increase in Ca²⁺ influx after stimulation with CAP as indicated by an increase in the fluorescence intensity of fluo-3 emission at 488-nm excitation (Fig. 8). This demonstrated that TRPV1 in primary cultured DRGNs was functional. As shown in Fig. 8A, DRGNs responded to 0.1 μM CAP with a much greater change in fluo-rescence intensity when pretreated with poly:IC, gardiquimod, or ODN 1826 for 16 h (Fig. 8A). Also, activation of TLR3, TLR7, or TLR9 resulted in marked increases in the sensitivity of TRPV1 to various concentrations of CAP (0.03, 0.1, and 1 μM) (Fig. 8B) (p = 0.008, p = 0.039, and p = 0.041, respectively). We further confirmed the enhanced sensitization of TRPV1 induced by TLR ligands by using an endogenous ligand of TRPV1, Ana. DRGNs consistently responded to Ana with an enhanced Ca²⁺ influx when pretreated with poly:IC, gardiquimod, or ODN 1826 (Fig. 8C). The Ca²⁺ influx in neurons pretreated with TLR ligands was higher in the presence of 1.86, 5.57, or 16.7 μM Ana (Fig. 8C) (poly-IC p = 0.009, gardiquimod p = 0.029, or ODN 1826 p = 0.048). The Ca²⁺ influx induced by CAP in DRGNs was totally blocked by SB-366791 (Supplemental Fig. 1), a selective TRPV1 antagonist. Conversely, no Ca²⁺ influx in DRGNs was observed when TLR ligands alone were applied (Supplemental Fig. 2). These studies show that in addition to inducing the production of inflammatory pain-inducing mediators, TLR ligands also upregulated expression of functional TRPV1 pain signaling receptors.

**Sup ODN treatment blocks tumor-induced pain sensitivity**

Sup ODNs, which mimic the suppressive effect of self-DNA by decreasing the immune activating signals of TLR9, were tested in a mouse model of tumor-induced neuropathic pain for their ability to decrease temperature sensitivity. As can be seen in Fig. 9, fibrosarcoma tumor cells implanted near the sciatic nerve result in decreased time of paw withdrawal, indicating hypersensitivity to heat in the tumor-bearing mice. When compared with negative control or naive mice, the tumor-bearing mice show a significantly faster withdrawal from the hot plate that increases over time (p < 0.001). We were unable to evaluate longer time points because tumor-bearing mice begin to show stress by day 15 and must be euthanized. Treating the tumor-bearing mice with Sup ODNs, which block TLR9-mediated immune stimulation, resulted in an

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**FIGURE 7.** TRPV1 is expressed by DRGNs and relocates after TLR ligands stimulation. Confocal images of TRPV1 expressed by primary cultured mouse DRGNs are shown. DRGNs were stained with TRPV1 (green), neuron-specific β-III tubulin (red), and DAPI (blue). Shown are monochrome images of the green fluorescence channel and merged color images from all channels. A–D, Control (A), poly-IC (25 μg/ml) (B), gardiquimod (3 μg/ml) (C), and ODN 1826 (32 μg/ml) (D) stimulation for 16 h induced TRPV1 expression in DRGNs. Scale bars, 50 μm. E. The average intensity of TRPV1 in the neuron surface and dendrites. Image intensity analysis was performed using ImageJ software. Statistical analysis was performed using Student t test for two-group comparisons. **p < 0.01 (compared with control).
increase in time of paw withdrawal from the heat challenge, indicating a reduction in heat sensitivity. Fig. 9 shows a dose response from no treatment to treatment with 320 μg/mouse Sup ODN. Beginning at the 20 μg/mouse dose, the difference between the negative control and the tumor-bearing and treated groups becomes suppressed, indicating that treatment with Sup ODN reduced tumor-induced pain. The reduction in heat sensitivity becomes significant at the 80 μg/mouse dose. This was not due to inhibition of tumor growth because a reduction in tumor growth was not observed until the highest tolerated dose (320 μg/mouse) of Sup ODN (data not shown). The paw withdrawal latencies for naive mice receiving 320 μg/mouse Sup ODN were not significantly different from those of the control group (data not shown). Thus, our data indicate that suppression of TLR9 leads to reduced sensitivity to heat in a neuropathic pain model despite the presence of a growing tumor when the Sup ODNs are delivered outside of the CNS. Our observations suggest a connection between suppression of a heat-activated pain receptor in the peripheral nervous system, when a mouse is treated with a suppressive TLR9 oligonucleotide.

Discussion

One of the cardinal signals of inflammation is pain. Pathogens, injury, and stressors stimulate TLRs on innate immune cells thereby initiating the proinflammatory signal-transduction pathways that ultimately trigger cytokine production. In the current study, we found that TLRs, which are also expressed by peripheral neuronal cells in response to synthetic ligands, produce cytokine and chemokine protein products, such as IL-1α, IL-1β, RANTES, mean ± SEM (n = 30). The data were analyzed by two-way ANOVA. *p < 0.05, **p < 0.01 (compared with control).
and IP-10, which have previously been shown to act as pain mediators (5, 6, 36–38).

The current results provide the first evidence, to our knowledge, that primary cultured mouse DRGNs constitutively express TLR3/7/9 and respond to their ligands. We focused on embryonic DRGNs because the resulting cultures generate highly pure (>95%) single neurons, thereby allowing us to investigate selectively neuronal TLR expression and responsiveness to TLR ligands. Our results indicate that DRGNs have the potential to recognize viral and cellular products and initiate an inflammatory response in the peripheral nervous system without prior activation of immune cells to produce proinflammatory cytokines. Indeed, in our study, stimulation by the TLR ligands (poly-IC, gardiquimod, and ODN 1826) induced cytokine (IL-1α and IL-1β) and chemokine (CCL5 and CXCL10) gene expression and protein production by DRGNs. Moreover, the activation of TLRs produced PGE2, which acts as a pain inducer. TLR ligand stimulation also enhanced expression and translocation of TRPV1. Furthermore, TRPV1 relocated from the DRGN cell bodies into dendrites after TLR ligand stimulation. TRPV1 relocalization has been reported to be involved in the development of hyperalgesia in vivo (39, 40).

Notably, pretreatment with TLR ligands also enhanced the TRPV1-mediated Ca2+ influx induced by CAP in DRGNs. Thus, peripheral neurons function to bridge the innate immune and sensory systems.

Previous studies demonstrated that TLRs are widely expressed in the CNS, particularly by microglia (41). Activation of TLRs on microglia and astrocytes leads to production of cytokines, cellular adhesion molecules, chemokines, and the expression of surface Ags that result in a nervous system immune cascade. Therefore, TLRs also invoke inflammation in the nervous system (42, 43). TLRs expressed on microglia appear to trigger microglial activation, which might be a driving force of chronic pain. Acosta et al. have shown that LPS, by stimulating TRLR4, regulates the expression of the peptide nociceptin/orphanin FQ, which contributes to feeding behavior. These observations show that TLR4 potentially acts as a key initiator of behavioral responses mediated by DRGNs (44). In addition, immunohistochemical analysis of human and rat trigeminal neurons demonstrated that CAP-sensitive nociceptors express TLR4, thus enabling sensory neurons to respond to tissue levels of bacterial substances such as LPS (45).

Other cells in the peripheral nervous system, including Schwann cells, respond to TLR ligands by producing proinflammatory factors. Poly-IC is responsible for stimulating inducible NO synthase gene expression and NO production in Schwann cells, which exerts neurotoxic effects on DRGNs (46). Our results confirm and extend earlier observations that TLR3/7/9 are expressed by DRGNs (47). Our studies demonstrate that DRGNs respond to the TLR ligand stimulation, indicating that they are functional, and suggest that DRGNs through their response to TLR ligands mediate neuronal function.

Ca2+ influx induced by TRPV1 activation is one of the causes of pain perception in the nervous system (48). We observed Ca2+ influx in DRGNs after stimulation with CAP or Ana, which indicates that the primary cultured DRGNs respond to TRPV1 ligands. SB-366791, a selective TRPV1 antagonist, totally blocked Ca2+ influx, suggesting that Ca2+ influx was mediated by TRPV1. A dramatic increase in Ca2+ was observed in DRGNs after pretreatment with TLR ligands. Therefore, TLR ligands not only upregulated TRPV1 expression but also enhanced its activity. At the same time, Ca2+ influx through TRPV1 in the nociceptive neuron endings is known to cause the release of mediators of inflammation such as substance P and calcitonin gene-related peptide. Substance P and calcitonin gene-related peptide synergize to induce a phenomenon called neurogenic inflammation that results in increased blood–brain barrier permeability (49). Investigating the effect of delivering TLR agonists to the peripheral nervous system on blood–brain barrier permeability will require future in vivo studies.

Inflammation induces neuropathic pain, which is experienced as hypersensitivity to thermal, mechanical, or chemical stimuli. The model of neuropathic pain used in this study, implantation of fibrosarcoma S-180 cells near the sciatic nerve, is thought to induce pain through two pathways, mechanical restriction of the nerve (28) as the tumor grows and tumor-produced soluble factors like PGE2 (50) and chemokines (51). In this study, we have shown that suppressive oligonucleotides that block TLR9-mediated immune activation (22) also block sensitivity to heat, which is thought to be mediated by TRPV1 (52). Taken with our in vitro data, these in vivo data indicate that there is functional cross-talk between innate immune receptors (TLR) and pain sensory receptors (TRPV1) in peripheral neurons.

In summary, our findings provide an intriguing example of a set of receptors shared between cells of the immune and the nervous systems that are likely to enhance the responses of both systems. These studies show that TLRs have the potential to have both direct and indirect effects on pain initiation and regulation. Therefore, DRGNs and TLRs are likely to be important contributors to chronic pain and a rewarding target in the development of novel therapeutic strategies in the prevention of development and in reduction of chronic pain.

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Disclosures
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References


42. Pedras-Vasconcelos, J., M. Puig, and D. Verthelyi. 2009. TLRs as therapeutic targets in CNS inflammation and infection. *Front Biosci (Elite Ed)* 1: 476–487.


