The CNS role of Toll-like receptor 4 in innate neuroimmunity and painful neuropathy

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Neuropathic pain remains a prevalent and persistent clinical problem because of our incomplete understanding of its pathogenesis. This study demonstrates for the first time, to our knowledge, a critical role for CNS innate immunity by means of microglial Toll-like receptor 4 (TLR4) in the induction phase of behavioral hypersensitivity in a mouse and rat model of neuropathy. We hypothesized that after L5 nerve transection, CNS neuroimmune activation and subsequent cytokine expression are triggered by the stimulation of microglial membrane-bound TLR4. To test this hypothesis, experiments were undertaken to assess tactile and thermal hypersensitivity in genetically altered (i.e., TLR4 knockout and point-mutant) mice after L5 nerve transection. In a complementary study, TLR4 antisense oligodeoxynucleotide (ODN) was administered intrathecally to L5 spinal nerve injured rats to reduce the expression of spinal TLR4. Both the genetically altered mice and the rats treated with TLR4 antisense ODN displayed significantly attenuated behavioral hypersensitivity and decreased expression of spinal microglial markers and proinflammatory cytokines as compared with their respective control groups. This finding shows that TLR4 contributes to the initiation of CNS neuroimmune activation after L5 nerve transection. Further understanding of this early, specific, innate CNS/microglial response and how it leads to sustained glial/neuronal hypersensitivity may point to new therapies for the prevention and treatment of neuropathic pain syndromes.

Abbreviations: TLR4, Toll-like receptor 4; ODN, oligodeoxynucleotide; KO, knockout; GFAP, glial fibrillary acid protein; COX-2, cyclooxygenase 2.

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Rats. Male Sprague–Dawley rats \( (n = 48) \) purchased from Harlan (Indianapolis) were used. All weighed 200–250 g at the time of surgery. The Institutional Animal Care and Use Committee at Dartmouth College approved all experimental protocols. In accordance with the guidelines set forth by the International Association for the Study of Pain, efforts were made throughout to minimize animal discomfort and to use the fewest animals needed for statistical significance. Animals were housed on a 12-h light, 12-h dark cycle with food and water available ad libitum.

Surgery. Animals were anesthetized with halothane in an O\(_2\) carrier (induction, 4% and maintenance, 2%). A small incision to the skin overlying L5-S1 was made, followed by retraction of the paravertebral musculature from the vertebral transverse processes. The L6 transverse process was partially removed, exposing the L4 and L5 spinal nerves. The L5 spinal nerve was identified, lifted slightly, and transected. The wound was irrigated with saline and closed in two layers with 3-0 polyester suture (fascial plane) and surgical skin staples.

Behavioral Testing. For mice, mechanical sensitivity was assessed by applying 0.008- and 0.015-g von Frey filaments (Stoelting, Wood Dale, IL) on the plantar surface of the ipsilateral hind paw. For rats, 2- and 12-g von Frey filaments were used. These stimuli are normally nonnoxious. Allodynia was characterized as the number of paw withdrawals in three sets of 10 stimulations each, and was tested on days 1, 3, 5, 7, 10, and 14 after surgery. For mice and on days 1, 3, 5, and 7 for rats. Thermal sensitivity for baseline was determined by using paw-withdrawal latencies to radiant stimuli are normally nonnoxious. Allodynia was characterized as the number of paw withdrawals in three sets of 10 stimulations each, and was tested on days 1, 3, 5, 7, 10, and 14 after surgery. For mice and on days 1, 3, 5, and 7 for rats. Thermal sensitivity was assessed with a radiant heat source. The plantar surface of the ipsilateral hind paw was exposed to radiant stimuli of 49°C. Three tail-flick and paw-withdrawal latencies were obtained per animal for each testing session. Animals were tested for baseline responses three times before undergoing the L5 spinal nerve transection surgery.

Intrathecal Oligodeoxynucleotide Administration. We conducted a set of experiments by using the L5 spinal nerve transection model in rats. TLR4 antisense ODN, mismatch ODN, and a random control oligonucleotide labeled with FITC were custom-made by Biognostik (Göttingen, Germany). The oligonucleotide was resuspended in sterile PBS at a final concentration of 1 \( \mu \text{g/µl} \) for mismatch ODN and 2 \( \mu \text{g/µl} \) for antisense ODN. The rats were divided into three groups based on the final amount of ODN intrathecally administered. In the first group, rats were administered antisense ODN (10 \( \mu \text{g/day}; n = 8 \)), mismatch ODN (10 \( \mu \text{g/day}; n = 8 \)), or saline \( (n = 8 \) ), and tested separately. In the second group, rats were administered antisense ODN (20 \( \mu \text{g/day}; n = 8 \)), mismatch ODN (20 \( \mu \text{g/day}; n = 8 \)), or saline \( (n = 8 \) ). All rats in both groups underwent L5 nerve transection surgery, and, after daily behavioral testing that took place between 8:00 and 10:00 a.m., were administered ODN intrathecally by means of lumbar puncture under brief inhalational anesthesia for 7 days starting 1 day before surgery. In the third group, 20 \( \mu \text{g} \) of FITC-labeled random oligonucleotide was injected intrathecally by means of lumbar puncture in three rats. These rats were killed at 4, 8, or 12 h after injection to determine the optimal cellular uptake time of FITC-labeled oligonucleotide. The injection volume was 10 \( \mu \text{l} \) followed by a 15-\( \mu \text{l} \) sterile PBS wash.

The ODN solutions were aliquoted in sterile 1.5-ml Eppendorf tubes. The aliquots were stored at \(-20^\circ\text{C}\), and three aliquots were taken out daily during the 7 days of intrathecal administration. The experimenter was blind to their content throughout the study. Behavioral testing was carried out 1 h before the administration of TLR4 antisense ODN, mismatch ODN, or saline. All rats in groups 1 and 2 were killed on day 7 after surgery.
Diego). A monoclonal antibody for CD11b was used to label the time-course expression of CD11b/CR3 on activated microglia (1:500 working dilution, Serotec).

**Statistical Analysis.** The statistical significance of differences between TLR4 KO, point-mutant, TLR4 antisense ODN-treated, and control animals was determined by using multivariate two-way ANOVA followed by post hoc Bonferroni analysis. All statistical analyses were performed by using PRISM 4.01 (GraphPad, San Diego). A P value of <0.05 was considered significant.

**Results**

**TLR4 is Critical for Pain Induction After Nerve Injury.** The TLR4 KO mice (C57BL/10ScSnJ; n = 21) and point-mutant mice (C3H/HeJ; n = 8) displayed significantly attenuated mechanical allodynia compared with their respective wild-type controls (C57BL/10ScSnJ; n = 15 and C3H/HeJ; n = 7) for 0.008-g (P < 0.001) and 0.015-g (P < 0.001) von Frey filament stimulations beginning at day 1 after surgery (Fig. 1 a and b). Fig. 1d shows that TLR4 KO and point-mutant mice also displayed a significantly attenuated response to heat for days 1–7 (P < 0.05) and 10–14 after surgery (P < 0.001). Fig. 1d shows that the tail-flick response to immersion in 49°C water was also significantly attenuated for these mice for days 1–7 (P < 0.05) vs. KO; two-way ANOVA followed by Bonferroni post hoc test.)

**Knockout of TLR4 Leads to Attenuation in Spinal Glial Activation.** A 3- to 5-fold decrease in expression of mRNA for CD11b and CD14...
was observed in TLR4 KO mice compared with the wild-type control group beginning at day 3 after surgery (Fig. 2a and b; \( P < 0.001 \)). Fig. 2c shows graded, significant up-regulation of TLR4 mRNA in the wild-type control group (\( P < 0.001 \)). No TLR4 mRNA was detected in the TLR4 KO mice. Messenger RNA for the astrocytic activation marker glial fibrillary acid protein (GFAP) also decreased in TLR4 KO mice relative to the wild-type control group, starting at day 7 after surgery (Fig. 2d; \( P < 0.001 \)).

**TLR4: Link Between Innate Immunity and Spinal Proinflammatory Cytokine Expression.** Significantly (3- to 5-fold) lower spinal expression of mRNA for IFN-\( \gamma \), IL-1\( \beta \), and TNF-\( \alpha \) was observed after injury in the TLR4 KO mice as compared with the wild-type control group (Fig. 3; \( P < 0.001 \)).

**Relationship Between Microglial Activation and TLR4.** In injured wild-type mice, we observed robust immunoreactive staining of CD11b/CR3 throughout the dorsal horn ipsilateral to the L5 nerve transection (laminae I-IV) on days 3, 7, and 14 after surgery. By contrast, CD11b/CR3 immunoreactivity was reduced almost to baseline levels in the ipsilateral dorsal horn of injured TLR4 KO mice (Fig. 4). These immunohistochemical protein data support the mRNA findings for CD11b (see Fig. 2a).

**Spinal TLR4 Antisense ODN-Attenuated Behavioral Hypersensitivity in Rats.** We confirmed that FITC-labeled random control ODN was incorporated into the spinal cord. Colabeling with DAPI demonstrated the proximity of the FITC-labeled ODN to the nucleus, showing that the modified ODN was incorporated into the CNS parenchyma (see Fig. 7, which is published as supporting information on the PNAS web site). Daily intrathecal injection of 10 \( \mu \)g of TLR4 antisense ODN resulted in moderate but significant attenuation of both mechanical allodynia and thermal hyperalgesia; more significant attenuation was observed with 20-\( \mu \)g daily injections (Fig. 5; \( P < 0.001 \)). Daily injections of saline or of 10 or 20 \( \mu \)g of mismatch ODN did not alter mechanical or thermal hypersensitivity.

**TLR4 Antisense ODN Leads to Decreased Microglial Activation and Proinflammatory Cytokine Expression.** Because of the potential for TLR4 antisense ODN backbone toxicity, the maximum daily intrathecal administration of TLR4 antisense ODN was 20 \( \mu \)g. This dosage provided a 56% decrease in spinal TLR4 mRNA expression, as shown in Fig. 6a (\( P < 0.001 \)). Decreased expression of TLR4 paralleled the decreased expression of the microglial activation markers CD11b (51%) and CD14 (44%) (\( P < 0.001 \)). The decrease in TLR4 also led to a significant decrease in proinflammatory cytokines, i.e., TNF-\( \alpha \) (17%), IL-6 (52%), and IL-1\( \beta \) (53%); \( P < 0.001 \) in all cases in TLR4 antisense ODN-treated rats as compared with rats treated with saline or mismatch ODN (Fig. 6b).
the activation of NF-nociceptors to transmit low-intensity nonnoxious stimuli. To a hyperexcitable state with intense nociceptive input to the metabolism (23). At the spinal cord level, these alterations lead cyclooxygenase and lipoxygenase pathway of the arachidonic acid or unsaturated fatty acids, high-extracellular potassium, seroto-

Discussion

The data presented herein demonstrate for the first time, to our knowledge, a key role for microglial TLR4 in the induction of behavioral hypersensitivity in rodent models of neuropathy. Our data also show that the mRNA expression of the microglial activation markers, TLR4, CD11b/CR3, and CD14, were only elevated at the initiation phase of behavioral hypersensitivity (days 3 and 7). Conversely, the astrocytic activation marker GFAP showed an opposite pattern with a graded increase in the mRNA expression level at later time points (days 7 and 14). These results are consistent with our previous finding that suggests microglia are involved in the initiating phase of behavioral hypersensitivity, whereas astrocytes are involved in the maintenance phase (18, 22).

After L5 nerve transection injury, mediators are released or activated, causing secondary swelling and damage to neurons. Such mediators include: ATP, glutamate, acidosis, free saturated or unsaturated fatty acids, high extracellular potassium, serotonin, bradykinin, substance P, histamine, and products from the cyclooxygenase and lipooxygenase pathway of the arachidonic acid metabolism (23). At the spinal cord level, these alterations lead to a hyperexcitable state with intense nociceptive input to the dorsal horn and the chemical sensitization of high-threshold nociceptors to transmit low-intensity nonnoxious stimuli.

One specific example of a TLR4 ligand released after nerve injury are saturated fatty acids, which have been shown to induce the activation of NF-xb and the up-regulation of cyclooxygenase 2 (COX-2) and other inflammatory markers upon interacting with membrane bound TLR4 of monocyte/macrophage such as micro-
glia (24, 25). The up-regulation of COX-2 and its contribution to central sensitization after various types of peripheral nerve injury has been well established (26–28). It has also been shown that the induction of NF-xb and the up-regulation of COX-2 was inhibited by dominant-negative TLR4 (25, 29, 30). These previous findings suggest that the modulation of COX-2 expression by fatty acids via the TLR4-derived signaling pathways is one potentially important pathway that links peripheral nerve injury to behavioral hypersensitiv-

We used two strategies to investigate the role of TLR4 in the induction of behavioral hypersensitivity after L5 nerve transection. First, two strains of genetically altered mice were used to examine the effects of complete TLR4 gene deletion and of functionally mutated TLR4 protein, respectively. Second, intrathecal injection of antisense ODN in rats was used to examine the effects of reduced CNS/spinal TLR4 expression. We demonstrated that after L5 nerve transection, functional knockout, or point mutation of the TLR4 gene in mice (i) significantly attenuates L5 nerve transection-induced tactile and thermal hypersensitivity, (ii) reduces spinal microglial activation as assayed by using CD11b/CR3 immunoreactivity and expression of mRNA for microglial activation markers, (iii) reduces expression of mRNA for spinal proinflammatory cytokine, and (iv) significantly decreases expression of mRNA for GFAP. These results agree with the previously observed correlation between microglial and astrocytic activation and the initiation and maintenance of behavioral hypersensitivity in rats (18, 22). Furthermore, we have previously shown that expression of mRNA for CD11b precedes sustained up-regulation of GFAP in the lumbar spinal cord in a similar neuropathic pain model in rat (18).
We have also shown that TLR4 antisense ODN intrathecally administered in rats (i) produces a significant and dose-related attenuation of L5 nerve transection-induced tactile and thermal hypersensitivity, (ii) reduces expression of mRNA for microglial markers, and (iii) reduces expression of mRNA for spinal proinflammatory cytokines.

It is important to note, however, that neither set of experiments in this study completely reversed L5 nerve transection-induced behavioral hypersensitivity. This finding suggests a potential role for other glial receptors or glial mediators such as CD14/MD-2, CD11b/CR3, or unique glial/neuronal signals like fractalkine in the initiation of behavioral hypersensitivity (31, 32). Thus, our results underscore the complexity of CNS cascades and mediators that may underlie neuronal sensitization, the pathologic correlate to chronic pain.

The involvement of TLR4 in the CNS innate immune response is now well established (12, 14). Previous studies by our laboratory and others have shown that TLR4 is mainly expressed by microglia (52, 123). Importantly, we have and others have shown that TLR4 is mainly expressed by microglia is now well established (12, 14). Previous studies by our laboratory and others have shown that TLR4 is mainly expressed by microglia is now well established (12, 14). Importantly, we have shown that spinal mRNA for TLR4 is increased after L5 nerve transection in the absence of LPS (18, 22). These data, together with the results presented herein, provide information related to a component of a mechanistic link between microglial activation and behavioral hypersensitivity.

The CNS innate immune response includes rapid activation of immune effector cells and the release of proinflammatory cytokines such as TNF-α, IL-1β, and IFN-γ through the activation of TLR4 MyD88-dependent or -independent pathways (34). Furthermore, the expression of proinflammatory cytokines by activated glia after L5 nerve transection has also been shown to be a major factor contributing to the establishment of behavioral hypersensitivity (4). Given that the knockout or knockdown of TLR4 expression leads (as shown in the present study) to attenuation of behavioral hypersensitivity, decreased glial activation, and decreased expression of proinflammatory cytokines, our picture of this aspect of the etiology of behavioral hypersensitivity is significantly clarified. Microglial activation occurs through TLR4 and leads to the enhanced expression of spinal proinflammatory cytokines. Cytokines, in turn, whether alone or by inducing the expression of known algic mediators such as substance P, nitric oxide, nerve growth factor, glutamate, and prostaglandins, produce central sensitization (i.e., enhanced excitation and responsiveness of spinal neurons due to activity-dependent changes in those neurons), and thus, to behavioral hypersensitivity (22). Recent work has shown direct involvement of TLR4 in the expression of costimulatory molecules, MHC class II, chemokines, integrins, and adhesion molecules, all of which contribute to central sensitization, and thus, to behavioral hypersensitivity (31, 32, 35–41). The present study has also demonstrated that a decrease of TLR4 leads to a decrease in CD11b/CR3 and in proinflammatory cytokine expression. That is, TLR4 is a microglial sensor that triggers glial activation and the dynamic CNS immune response that ensues in response to L5 nerve transection. This finding agrees with previous studies showing that a deficiency in CD11b/CR3 seriously compromises innate immunity through a syndrome clinically known as leukocyte adhesion deficiency. This syndrome provides compelling evidence for the importance of β2-integrins, including CD11b/CR3, in mediating leukocyte adhesive, migratory, and phagocytic activities in response to inflammatory stimuli, and underlines their role in facilitating first-line host defense (42–44).

All these findings support a CNS role for TLR4 and innate immunity in the etiology of neuropathic pain. The ability of TLR4 to activate a pathway leading to central sensitization and nerve injury-induced behavioral hypersensitivity may provide an opportunity for regulating glial activation, and thus, alleviating chronic pain due to nerve damage.

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