Characterization of Acute and Chronic Neuropathies Induced by Oxaliplatin in Mice and Differential Effects of a Novel Mitochondria-targeted Antioxidant on the Neuropathies

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ABSTRACT

Background: Oxaliplatin, a chemotherapeutic agent used for the treatment of colorectal cancer, induces dose-limiting neuropathy that compromises quality of life. This study aimed to reproduce, in mice, patients’ symptoms of oxaliplatin-induced neuropathy and to observe effects of SS-31, a mitochondria-targeted antioxidant on the neuropathy.

Methods: Neuropathy was induced by single or repeated injections of oxaliplatin. Cold and mechanical hypersensitivities were assessed by 15°C-cold plate, temperature preference, and von Frey tests. Morphology of peripheral nerves and dorsal root ganglia, expression of spinal cord c-Fos, density of intraepidermal nerve fibers, and levels of dorsal root ganglion–reactive oxygen/nitrogen species were examined. SS-31 was administered concomitantly or after oxaliplatin injections.

Results: Single injection of oxaliplatin induced cold hypersensitivity in forepaws but not in hind paws which resolved within days (maximal forepaw shakes: 28 ± 1.5 vs. 9.3 ± 1.6/150 s, mean ± SEM, \( P < 0.001 \), \( n = 6 \) per group). Oxaliplatin administered mice disfavored 10° and 15°C plates more than control. Paw stimulation at 15°C induced c-Fos–positive cells within superficial laminae of the dorsal horn in C7–T1 segments. Weekly administrations induced gradual development of persistent mechanical allodynia in the hind paws (minimal mechanical threshold: 0.19 ± 0.08 vs. 0.93 ± 0.11 g, \( P < 0.001 \), \( n = 10 \) per group). Microscopy revealed no overt morphological changes in peripheral nerves and dorsal root ganglia. Concomitant SS-31 administration with repeated oxaliplatin administration attenuated both cold and mechanical hypersensitivity. Decrease in intraepidermal nerve fibers and increase in dorsal root ganglion–reactive oxygen/nitrogen species were also attenuated. Acute SS-31 administration after symptoms were established reversed only cold hypersensitivity.

Conclusion: This model of oxaliplatin-induced neuropathy mimicked patients’ conditions. SS-31 has potential to prevent both acute and chronic neuropathies but is only helpful in treatment of acute neuropathy. (Anesthesiology 2014; 120:459-73)

OXALIPLATIN (L-OHP) is a platinum-based chemotherapeutic agent used for the treatment of advanced colorectal cancer.1–3 Neurotoxicity is the most common toxicity of oxaliplatin, manifesting two distinct neuropathies.3–11 Acute neuropathy, which is common and unique to oxaliplatin, occurs acutely after administration of each oxaliplatin dose and consists of reversible cold-induced dysesthesia/paresthesia of the hands and face but rarely of the feet.3,5 Patients experience symptoms when they touch moderately cold items that normally would not produce pain. This acute neuropathy is usually self-limiting and symptoms resolve in days, within each administration cycle. Chronic neuropathy gradually develops and intensifies after multiple administration cycles. Patients complain of ongoing dysesthesia/paresthesia of extremities and impaired sensory/motor coordination may also be present. The chronic neuropathy is similar to those seen with other platinum derivatives, and once developed, most patients continue to experience symptoms for months. Such side effects can seriously compromise patients’ quality of life and lead to changes in treatment to nonneurotoxic agents with obvious negative implications for disease outcomes.

Recently, multiple animal studies have been described that use various doses of oxaliplatin with various administration schedules. Some of these studies report that oxaliplatin...

What We Already Know about This Topic

• Oxaliplatin and other platinum-containing chemotherapeutics often cause a form of peripheral neuropathy reducing quality of life and limiting the dose of drug which can be tolerated.

What This Article Tells Us That Is New

• In mice, oxaliplatin causes sensitization to both cold and mechanical stimuli, most prominently in the forepaws.
• Administration of the antioxidant agent SS-31 reduced both the nociceptive sensitization and the accumulation of reactive oxygen species.
causes damage to cell bodies,12–15 alterations in nucleolus morphology,12 selective atrophy of subpopulation of dorsal root ganglion (DRG) neurons,16 and degeneration of peripheral nerve axons.12–17 However, different investigators have failed to show axonal degeneration.18 Because pathological changes may depend on doses and schedule of oxaliplatin administration,12,14 it is essential that the doses and schedule of administration in animal models used to study the neuropathies will produce the same condition as those in patients. Thus, the doses used should produce antitumor effects and the administration schedule should include rest periods that allow recovery from acute damage. The aim of this study was to develop such an animal model in mice and to investigate its neuropathic symptoms in detail so as to compare them with symptoms observed in patients. We used doses that had been reported to produce antitumor effects19–21 and set the schedule that would allow a significant degree of recovery from acute neuropathy within the cycle. We also confirmed the antitumor effects of the doses in mice given by our study schedule. Furthermore, using this model, we attempted to reveal possible morphological changes in the peripheral nerve and/or DRG neurons that may have relevance to the mechanism of the neuropathic symptoms. In addition, in wake of recent reports by other investigators that show the involvement of mitochondrial dysfunction and oxidative stress in chronic oxaliplatin-induced neuropathy,22–24 we investigated the effects of SS-31, a novel mitochondria-targeted antioxidant, in this model. SS-31 is a tetrapeptide that targets and concentrates on the inner mitochondrial membrane, the site of electron transport chain, and reactive oxygen species (ROS) production.26,27 SS-31 has been demonstrated to be highly effective in several animal disease models associated with mitochondrial dysfunction and oxidative stress.28–34 We examined whether SS-31 can protect against the development of acute and chronic neuropathies and also whether it can alleviate the symptoms after each neuropathy has been established.

Materials and Methods

Experiments were approved by the Institutional Animal Use Committee of Teikyo University, Tokyo, Japan, and were conducted in accordance with the National Institutes of Health guidelines and the International Association for the Study of Pain Committee for Research and Ethical Issue guidelines for animal research.35 The experimenter was blinded to treatment in all behavioral experiments. The experimenter who performed the quantification in the morphological studies of peripheral nerves and DRGs was not blinded to treatment. In all other morphological quantifications, the experimenter was blinded to treatment.

Animals, Drugs, and Cell Line

Male mice, 9 weeks old at the time of first drug administration, were used in the experiments. BALB/c mice were used except for the experiment on antitumor effects of oxaliplatin in which SCID mice were used. All mice were housed on a 12:12 h dark–light cycle with food and water ad libitum. Oxaliplatin was obtained from Yakult Co., Ltd. (Tokyo, Japan). Oxaliplatin was dissolved in distilled water and was injected intraperitoneally in a volume of 0.1 ml/10 g mouse weight. SS-31 (H-D-Arg-2,6-dimethylTyr-Lys-Phe-NH2) was obtained from Stealth Peptides, Inc. (Newton Centre, MA). SS-31 was dissolved in normal saline for continuous subcutaneous administration at a rate of 0.1 μl/h or in a volume of 0.1 ml/10 g mouse weight as subcutaneous injections. A human colorectal cell line (HCT116) was a generous gift from Dr. Soichiro Murata, M.D., Ph.D. (Associate Professor, Department of Surgery, Tsukuba University Graduate School of Medicine, Tsukuba, Ibaraki, Japan). The cancer cell line was subdivided in multiple tubes for stock in liquid nitrogen immediately after possession. Stock cultures were grown in high-glucose Dulbecco Modified Eagle Medium containing 10% fetal bovine serum and 1% antibiotics. Cells were grown in growth medium at 37°C in a 95% air–5% CO2 humidified incubator.

Acute Neuropathy

Nocifensive Response to Moderately Cold Temperature.

To observe the development of nocifensive response to moderately cold temperature induced by oxaliplatin, we first examined paw-shaking behavior of mice placed on a cold plate (LHP-1700CP; TECA, Chicago, IL) set at 15°C (15°C-cold plate test) and studied the effects of different doses of oxaliplatin and the time courses of the effects after a single injection. The number of forepaw and hind paw shakes was counted during a 150-s test period while mice were placed on the cold plate (15°C-cold plate test). Testing was performed before any drug administration and 1, 2, 3, 4, 5, 7, 9, and 12 days after oxaliplatin (2, 5, or 15 mg/kg) or vehicle administration. We used the cold plate test in our study because it enables us to examine the response to a specific temperature. Paw-shaking behavior has been accepted as a nocifensive behavior in multiple pain tests in mice. Paw-shaking behavior is used as a parameter in the acetone test36 and is also an end point of the hot plate test.37 However, in the hot or cold plate test, if the animal stands by its hind limbs, the forepaws would not be stimulated by the plate. Thus in our study, to ensure that both forepaws and hind paws were stimulated by the cold plate, we placed a clear plastic cover with ventilation pores over the cold plate to produce a ceiling 3.5 cm from the cold plate so that mice would not be able to stand by their hind limbs and would place both forelimbs and hind limbs on the cold plate. Furthermore, to support the behavioral results obtained by the 15°C-cold plate test, c-Fos expressions in the spinal dorsal horn at the thoracic and lumbar levels were examined in mice whose forepaws and hind paws were stimulated by the cold plate set at 15°C (see Materials and Methods section,
Acute Neuropathy, c-Fos Expression in the Dorsal Horn after Moderately Cold Thermal Stimulation of the Paws in Oxaliplatin-administered Mice.

Temperature Preference. Change in temperature preference induced by a single injection of oxaliplatin was assessed by the two-plate temperature preference test.³⁹ Each mouse was placed in a chamber containing two identical, adjacent floor platforms (LHP-1700CP; TECA) with one set to a fixed temperature of 24°C (room temperature) and the other (test plate) set to one of the following different temperatures: 24°, 20°, 15°, 10°, 5°, or 0°C. Mice were free to explore, and the time spent on the test plate during a 10-min test period was measured. Testing was performed before any drug administration and 4 days after the administration of oxaliplatin (15 mg/kg), which was the time of peak effect determined from the above experiment that examined the time course of cold hypersensitivity. The 15 mg/kg dose of oxaliplatin was selected because it was an effective dose in the above experiment.

Effect of Weekly Repeated Administrations of Oxaliplatin on Cold Hypersensitivity. Oxaliplatin at 15 mg/kg was injected weekly for three cycles, and cold hypersensitivity was assessed 4 days after each injection by the number of paw shakes in the 15°C-cold plate test described above (see Materials and Methods section, Acute Neuropathy, Nocifensive Response to Moderately Cold Temperature).

c-Fos Expression in the Dorsal Horn after Moderately Cold Thermal Stimulation of the Paws in Oxaliplatin-administered Mice. To observe the activation of dorsal horn neurons by moderately cold thermal stimulation in oxaliplatin-administered mice, c-Fos expression in the spinal dorsal horn was examined.³⁹ Mice were given oxaliplatin (15 mg/kg) or vehicle, and 4 days later, 15°C thermal stimulations were applied to the paws. By using the cold plate set to a fixed temperature of 24°C, 20°C, 15°C, 10°C, 5°C, or 0°C, mice were free to explore, and the time spent on the test plate during a 10-min test period was measured. Testing was performed before any drug administration and 4 days after the administration of oxaliplatin (15 mg/kg), which was the time of peak effect determined from the above experiment that examined the time course of cold hypersensitivity. The 15 mg/kg dose of oxaliplatin was selected because it was an effective dose in the above experiment.

Effect of Weekly Repeated Administrations of Oxaliplatin on Mechanical Threshold. Mechanical thresholds were determined before and 4, 7, and 12 days after a single injection of oxaliplatin (15 mg/kg) or vehicle.

Fos-like Immunoreactivity of Dorsal Horn Neurons in Repeated Oxaliplatin-administered Mice. To observe whether dorsal horn neurons were activated after multiple weekly oxaliplatin administrations, some of the mice that were given nine weekly injections of oxaliplatin (each dose at 10 mg/kg) or vehicle in the above study were sacrificed for c-Fos immunohistochemical studies. Fos-like immunostaining as described above was performed in L4–5 segments of the spinal dorsal cord excised from the mice 4 days after the last injection.

Morphological Studies of Peripheral Nerves and DRGs Some of the mice that underwent behavioral testing after repeated administrations of oxaliplatin were sacrificed for light and electron microscopic studies on the last day of testing. Each mouse was deeply anesthetized with pentobarbital and perfused intracardially with saline followed by a fixative solution which contained 4% paraformaldehyde in 0.01 M phosphate buffer saline (PBS). The C7–T1 (input from the forepaws) and L4–5 (input from the hind paws) segments of the spinal cord were excised for immunohistochemical studies. The excised spinal cord segments were processed and sliced by methods reported previously.⁴⁰ Antibodies against c-Fos (rabbit, polyclonal; Oncogene Research Products, San Diego, CA) were used. The sections were observed under a fluorescence microscope. The number of Fos-like immunoreactive nuclei in the superficial laminae of the ipsilateral dorsal horn in three random sections per segment was counted and averaged.
Effects of SS-31 Treatment on Oxaliplatin-induced Neuropathy

Effects of Continuous Administration of SS-31 during Repeated Oxaliplatin Administrations. SS-31 at 5 mg·kg\(^{-1}\)·day\(^{-1}\) or vehicle was continuously administered via subcutaneously implanted Alzet 1004 Micro-Osmotic Pumps (Alzet, Cupertino, CA). The pump was implanted 2 days before the first oxaliplatin injection to allow the infusion rate of the pump to stabilize. Mice were given three weekly administrations of oxaliplatin (15 mg/kg) and were tested 4 days after each injection for cold hypersensitivity and mechanical allodynia by the 15°C-cold plate test and the von Frey hair test, respectively (see Materials and Methods section, Acute Neuropathy, Nociceptive Response to Moderately Cold Temperature and Chronic Neuropathy).

Other mice implanted with Alzet pumps filled with SS-31 or vehicle and given repeated administrations of oxaliplatin as above were sacrificed on day 18 for ROS/reactive nitrogen species (RNS) assay of lumbar DRGs and intraepidermal nerve fiber (IENF) examination (see Materials and Methods section, ROS/RNS Assays of DRGs and Quantification of IENFs).

Effects of Acute Administration of SS-31 on Established Oxaliplatin-induced Neuropathic Symptoms and Dorsal Horn Neuron Activation. Mice were given a single dose of oxaliplatin (15 mg/kg). Four days after the injection, they were tested for cold allodynia by 15°C-cold plate test before and 1, 2, 4, and 6 h after the subcutaneous administration of SS-31 (10 mg/kg) or vehicle. Other mice were given three weekly injections of oxaliplatin (each dose at 15 mg/kg), and 4 days after the third injection, mechanical thresholds were measured by the von Frey hair test before and 2 h after the subcutaneous administration of SS-31 or vehicle.

In addition, the effect of acute administration of SS-31 on the activation of dorsal horn neurons by moderately cold thermal stimulation in oxaliplatin-administered mice was examined by c-Fos immunohistochemistry of the spinal cord. Mice were given a single dose of oxaliplatin (15 mg/kg). On day 4, SS-31 (10 mg/kg) or saline was given subcutaneously, and 2 h later, 15°C thermal stimulations were applied to the paws as the above experiment. Fos-like immunostaining was performed in C7-T1 segments of the spinal cord as described above (see Materials and Methods section, Acute Neuropathy, c-Fos Expression in the Dorsal Horn after Moderately Cold Thermal Stimulation of the Paws in Oxaliplatin-administered Mice).

ROS/RNS Assays of DRGs
Lumbar DRGs were excised from mice anesthetized with sevoflurane and homogenized in PBS. Homogenates were subjected to centrifugation at 10,000g for 5 min to remove insoluble particles. The concentration of ROS and RNS liberated was measured using Oxiselect in vitro ROS/RNS assay kit (Cell Biolabs, Inc., San Diego, CA) according to the manufacturer’s instructions. The relative fluorescence of the samples and the standards were read at 480 nm excitation/530 nm emissions using a multilabel plate reader (Arvo, PerkinElmer, Yokohama, Japan). The ROS/RNS liberated by DRGs were calculated using a 2’,7’-dichlorodihydrofluorescein standard curve. Data were normalized to one DRG level and were expressed as percentage of the mean value of the control group.

Quantification of IENFs
Plantar skin specimens were excised from the hind paw between the calcaneous and the digital tori. The specimens were immediately soaked in 4% paraformaldehyde for overnight fixation and then transferred to 30% sucrose and left overnight at 4°C. The specimens were then embedded in TissueTek OCT compound (Sakura Finetek Europe B.V., Zoeterwoude, The Netherlands) and frozen and sliced on a cryostat into 25 μm sections. The sections were collected in PBS and processed by a free-floating protocol. The sections were incubated in a blocking solution that consisted of 0.5% normal goat serum and 0.3% Triton-X100 in PBS for 30 min at room temperature. They were then incubated overnight at 4°C in primary antibodies in the blocking solution. Antibodies against protein gene-product 9.5 (rabbit, affinity purified; Enzo Life Sciences, Farmingdale, NY) was used. Following this step, the sections were incubated in biotinylated goat anti-rabbit IgG (Vector Laboratories, Belmont, CA) solution for 90 min at room temperature and then incubated with Alexa Fluor 488 streptavidin conjugate (Molecular Probes, Eugene, OR) for 60 min at room temperature. Between each step, the sections were rinsed with PBS three times. The sections were observed under a fluorescence microscope. The number of IENFs per millimeter of the epidermal border was counted in three random sections and averaged for each mouse.

Antitumor Effect of Oxaliplatin
HCT116 cells (1 × 10⁶) were implanted subcutaneously into the right thighs of SCID mice. Ten days after implantation, mice were randomly divided into five groups and were given three weekly administrations of oxaliplatin doses at 2, 5, 10, or 15 mg/kg or vehicle. Four days after the third injection, the mice were sacrificed and the tumors were excised and weighed.

Statistical Analysis
Statistical analyses were carried out with SigmaPlot statistical software package for Windows (version 11.0; Systat, San Jose, CA). Data were analyzed using a one-way or two-way ANOVA for repeated measures followed by the Bonferroni-corrected t test or paired t test, where appropriate. A two-tailed P value less than 0.05 was considered significant. Post hoc testing was only reported when statistically significant main effects were observed. There were no missing data for all analyses.
Results

Acute Neuropathy

Nocifensive Response to Moderately Cold Temperature. In mice given a single injection of oxaliplatin at 15 mg/kg, the number of forepaw shakes in the 15°C-cold plate test significantly increased compared with control mice by 2 days after injection. The effect peaked 4 days after injection and returned to control level by 9 days after injection (fig. 1A). None of the mice presented shaking, lifting, or licking of the hind paws. Single injection of oxaliplatin at 2 and 5 mg/kg did not have any effects in the 15°C-cold plate test.

Temperature Preference. In the temperature preference test, when the two plates were set at the same temperature (24°C), neither oxaliplatin- (15 mg/kg) nor vehicle-administered mice displayed any preference. When the test plate was cooled to 20°C or below while the adjacent plate's temperature was fixed to 24°C, both oxaliplatin- and vehicle-administered mice showed a preference for the warmer plate. The preference was not different between the two groups when the test plate was set at 20°C, but when it was set at 15° or 10°C, the oxaliplatin-administered mice showed a greater preference to the warmer plate compared with the vehicle-administered mice (fig. 1B). No difference in preference was present when the test plate's temperature was set below 10°C.

Effect of Weekly Repeated Administrations of Oxaliplatin on Cold Hypersensitivity. The effect of three weekly administrations of oxaliplatin (each dose at 15 mg/kg) on the 15°C-cold plate test is shown in figure 1C. In the oxaliplatin-administered mice, the number of forepaw shakes significantly increased compared with the vehicle-administered mice when tested 4 days after each oxaliplatin injection. The number of forepaw shakes did not further increase by repeating the oxaliplatin injections (day 4 vs. day 11: P = 1.000; day 4 vs. day 18, P = 0.120; day 11 vs. day 18, P = 0.216). The number of forepaw shakes significantly decreased 1 week later (day 18 vs. day 25; P < 0.001). Mice presented no or very few shaking and no licking or licking of the hind paws during any of the 15°C-cold plate tests performed during the course of the experiment (fig. 1C).

Fos-like Immunoreactivity of Dorsal Horn Neurons after Acute Neuropathy

Plasticity of the Nociceptive Neurons. The number of Fos-like immunoreactive cells in the superficial dorsal horn of the C7-T1 segments was significantly greater in oxaliplatin-administered mice as compared with vehicle-administered mice (fig. 2D). This difference was not present in the L4-5 segments (fig. 2D).

Chronic Neuropathy

Effect of Weekly Repeated Administrations of Oxaliplatin on Mechanical Threshold. No change in mechanical threshold was seen after a single dose of oxaliplatin (15 mg/kg; fig. 3A). However, in mice given three weekly administrations of oxaliplatin (each dose at 15 mg/kg), mice showed a decrease in mechanical threshold after the second and third doses of oxaliplatin as compared with control (fig. 3B). The effect started to gradually diminish 3 weeks after the last dose but was still present after 5 weeks (fig. 3B).

The effects of weekly administrations of lower oxaliplatin doses (5 and 10 mg/kg) on mechanical threshold are shown in figure 3C. Nine weekly administrations of 5 mg/kg doses (cumulative dose of 45 mg/kg) induced no significant decrease in mechanical threshold compared with vehicle administration. In animals given nine weekly administrations of 10 mg/kg doses, mechanical allodynia developed gradually. After four doses (cumulative dose of 40 mg/kg), the level of mechanical allodynia was similar to that after three doses of 15 mg/kg (cumulative dose of 45 mg/kg) and further progressed with additional doses (fig. 3C).

Fos-like Immunoreactivity of Dorsal Horn Neurons in Repeated Oxaliplatin-administered Mice. The L4-5 segments of the spinal cord were harvested from mice after nine weekly administrations of 10 mg/kg doses of oxaliplatin or vehicle. Fos-like immunoreactive cells were not present in the dorsal horn of the spinal cord in either oxaliplatin- or vehicle-administered mice.

Morphological Studies of Peripheral Nerves and DRGs

Microscopic examinations of the sciatic and brachial nerves and C8, T1, L4, and L5 DRGs harvested after three weekly administrations of 15 mg/kg doses of oxaliplatin or nine weekly administrations of 10 mg/kg doses of oxaliplatin revealed no overt morphological changes compared with vehicle administration (figs. 4 and 5). No difference in the number of myelinated and unmyelinated fibers of the sciatic nerve in vehicle-administered and oxaliplatin-administered mice was present (fig. 6A). Morphometric analysis of DRG neurons also revealed no difference between vehicle-administered and oxaliplatin-administered mice (fig. 6B). No morphological changes in Schwann cells and mitochondria within the nerve fibers and DRG neurons could be detected. Vacuolation of some mitochondria in peripheral nerve axons were observed in both vehicle- and oxaliplatin-treated mice. In contrast, significant loss of IENFs of the plantar skin was observed after repeated administrations of oxaliplatin (fig. 7).
Continuous Administration of SS-31 throughout Oxaliplatin Treatment. Continuous administration of SS-31 throughout the course of three weekly administrations of oxaliplatin decreased the number of forepaw shakes compared with control in the 15°C-cold plate test performed 4 days after each of the three weekly injections of oxaliplatin (fig. 8A). Continuous SS-31 treatment also attenuated the decrease in mechanical threshold compared with control when tested 4 days after the second and third injections of oxaliplatin (fig. 8B).
of IENFs induced by chronic oxaliplatin administration was also mitigated by continuous SS-31 treatment (fig. 7, C and D).

**Change in ROS/RNS Levels in DRGs.** Total ROS/RNS released from lumbar DRGs in mice treated with three weekly administrations of oxaliplatin doses (15 mg/kg) were significantly increased compared with control. This increase was significantly attenuated when mice received continuous SS-31 treatment concomitantly (fig. 9).

**Acute Administration of SS-31 after Development of Symptoms.** Acute administration of SS-31 in mice with cold hypersensitivity induced by a single injection of oxaliplatin resulted in alleviation of cold hypersensitivity tested by the 15°C-cold plate test at 1 h after SS-31 administration. The effect was still present at 4 h after administration (fig. 10). Acute administration of SS-31 also inhibited the expression of c-Fos in the superficial laminae of the dorsal horn in C7-T1 segments of the spinal cord induced by 15°C thermal stimulation in mice given a single injection of oxaliplatin (fig. 11). No effect on mechanical allodynia induced by three weekly injections of oxaliplatin was observed by acute SS-31 administration (fig. 12).

**Antitumor Effect of Oxaliplatin in Mice**

The weight of tumors in mice treated with three weekly doses of oxaliplatin at 5, 10, and 15 mg/kg doses (0.71 ± 0.13 g, 0.62 ± 0.25 g, and 0.48 ± 0.30 g, respectively, in mean ± SEM, n = 5 for each group) was significantly smaller than weight of tumors in mice treated with vehicle (1.71 ± 0.33 g, mean ± SEM, n = 5). Analysis was performed by a one-way ANOVA (P = 0.013) followed by Bonferroni multiple comparison tests (P < 0.05 for each comparison). The weight of tumors in mice treated with three weekly doses of oxaliplatin at 2 mg/kg (1.25 ± 0.19 g, mean ± SEM, n = 5) was not significantly different from control (P = 0.222).

**General Toxicity**

Single administration of oxaliplatin (15 mg/kg) induced a decrease in body weight compared with vehicle administration from day 2 to day 9 (P < 0.05). Three weekly administrations of 15 mg/kg doses (cumulative dose of 45 mg/kg) resulted in less weight gain compared with vehicle administration throughout the experiment (P < 0.01). The weight recovered after the cessation of oxaliplatin administration. Multiple weekly administrations of...
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Oxaliplatin-induced Neuropathy in Mice

5 and 10 mg/kg doses (cumulative doses of 45 and 90 mg/kg, respectively) did not result in any significant differences in weight gain compared with vehicle administration. There were no deaths in the oxaliplatin-administered mice irrespective of the dose used during the course of the experiments.

Discussion

In patients, acute neuropathy occurs abruptly after administration of oxaliplatin. Patients experience dysesthesia/paresthesia when they touch moderately cold items that normally would not produce pain.3,7,8 The symptom occurs in the hands and face and rarely in the feet.3,9 It diminishes during the rest period of each cycle and recurs with subsequent administrations.6 Single oxaliplatin administration to mice resulted in increased sensitivity to moderately cold temperature demonstrated by increased nocifensive behavior in response to 15°C stimulation. In naïve mice, the response peaked at 4 days and markedly diminished by 1 week after administration. With weekly administrations, cold hypersensitivity developed after each injection, but the intensity did not increase with repeated administrations, and the symptom quickly diminished after cessation of administration. The cold-induced behavior was present only in forepaws and not in hind paws. This was confirmed by examination of c-Fos expression in the dorsal horn. Cold stimulation (15°C) to forepaws and hind paws of oxaliplatin-treated mice invoked remarkable c-Fos expression in superficial laminae only in C7-T1 and not in L4-5 segments of the spinal cord. The distribution of c-Fos expression was in agreement with the localization of neurons receiving noxious inputs, and taken together with the behavior results, it suggests that the forepaws but not hind paws received noxious stimulation by 15°C stimulation. Noxious cold stimulation has been shown to invoke c-Fos expression in the superficial laminae of the dorsal horn.38 Temperature preference test was performed to determine the temperature range of the cold hypersensitivity. Oxaliplatin-administered mice showed a greater preference to the plate with a fixed temperature of 24°C compared with control when the test plate was set at 15° and 10°C, whereas preference did not differ between groups when the test plate was set below 10°C. It has been suggested that temperature threshold for eliciting cold pain is less than 10°C and that temperature of 10°C or higher is innocuous.42 Thus mice showed cold hypersensitivity at innocuous cold temperature. The temperature range also suggested that the cold hypersensitivity was likely mediated by transient receptor potential ankyrin 1 channels.43,44 The results taken together, the cold hypersensitivity in mice observed in this study mimicked cold allodynia observed in patients. Patients may experience cold-induced symptoms as early as the time of drug infusion. We could not detect such early manifestation of cold hypersensitivity in naïve mice given a single dose of oxaliplatin. There are no

Fig. 3. Mechanical thresholds in oxaliplatin-administered mice. Assessment was made by stimulation with von Frey filaments. The 50% mechanical withdrawal thresholds were determined using the up–down method (Chaplan et al.9). (A) Mechanical thresholds were determined before and 4, 7, and 12 days after a single injection of oxaliplatin (15 mg/kg) or vehicle (n = 10 for each group). (B) Oxaliplatin at 15 mg/kg or vehicle was injected weekly for three cycles, and mechanical thresholds were assessed 4 days after each injection and thereafter weekly for 5 more weeks (n = 10 for each group). (C) Oxaliplatin at 5 or 10 mg/kg or vehicle was injected weekly for nine cycles, and mechanical thresholds were assessed 4 days after each injection (n = 6 for each group). Data were given as the mean ± SEM and analyzed by two-way ANOVA for repeated measures (A, group effect: P = 0.326; time effect: P = 0.143; B, group effect: P < 0.001; time effect: P < 0.001; C, group effect: P < 0.001; time effect: P = 0.003) followed by Bonferroni multiple comparison tests where the main effects were significant. * P < 0.05, ** P < 0.01, *** P < 0.001 vs. corresponding time point of control group. OHP = oxaliplatin; VEH = vehicle.
Fig. 4. Light and electron microscopic photographs of sciatic nerves harvested from a chronic vehicle-administered mouse (A and B, respectively) and a chronic oxaliplatin-administered mouse (nine weekly administrations of 10 mg/kg doses) (C and D, respectively). The sciatic nerve specimens were harvested 4 days after the last administration. Scale bars, A and C: 50 μm; B and D: 1 μm.

Fig. 5. Electron microscopic photograph of L4 dorsal root ganglion neurons of vehicle-administered mice (A and B) and chronic oxaliplatin-administered mice (nine weekly administrations of 10 mg/kg doses) (C and D). Specimens were harvested 4 days after the last administration. Scale bars, A and C: 5 μm; B and D: 1 μm.
studies in patients examining the actual time course of cold hypersensitivity, that is, peak time and duration, thus we cannot ascertain that the time course observed in our study is comparable with patients. Furthermore, repeated administrations might cause change in time course such as early onset of cold hypersensitivity were having their first onset of the symptom. It is not clear whether patients with oxaliplatin administrations might cause change in time course such as early onset of cold hypersensitivity that diminished during the rest period of oxaliplatin administration, animals developed mechanical hypersensitivity as well as reduction in conduction velocity of sensory nerves, latter of which is also observed in patients with oxaliplatin-induced chronic neuropathy. Atal et al. reported that they could not detect any decrease in mechanical pain threshold in patients, whereas some patients complained of brush- or pressure-evoked pain. On the basis of our personal clinical experience, we have observed that although patients with oxaliplatin-induced ongoing dysesthesia/paresthesia feel numbness in their hands, they complain of increased dysesthesia when their feet are lightly touched. This may be the symptom that is manifested as mechanical allodynia in mice. Furthermore, the gradually developing and persistent nature of the mechanical allodynia in mice was similar to that of the symptoms of oxaliplatin-induced chronic neuropathy in patients. Thus, it is plausible to say that the mechanical allodynia observed in this study is a manifestation of oxaliplatin-induced chronic neuropathy and may be used as an indicator of the severity of chronic neuropathy in mice. An interesting finding of our study was that three weekly administrations of 15 mg/kg doses (cumulative dose: 45 mg/kg) did not. Although it is generally accepted clinically that the cumulative dose of oxaliplatin is the major factor that determines the occurrence of chronic neuropathy, our results show that the dose of each injection is also an important factor. This is consistent with current recommendation for management of oxaliplatin-induced neurotoxicity, that is, decrease dosage and increase number of administrations to reach the same cumulative dose.

Importantly, our study is the first to show that, in mice as in patients, a single dose of oxaliplatin induced acute cold hypersensitivity that diminished during the rest period of the administration cycle and that repeating these administration cycles induced chronic neuropathy. The doses of oxaliplatin used in our study were greater than those used in previous studies. However, based on our results and studies on antitumor effects of oxaliplatin in mice, the doses used in our study are appropriate because doses that produce
antitumor effects should be used to investigate side effects. Thus, our model mimics conditions of patients with oxaliplatin-induced neuropathy and may be useful to further investigate the neuropathy and to reduce variability in results as observed in previous studies that used variable protocols for administration.17,18,22,23,50–57

In this study, we detected no overt morphological changes in peripheral nerves and DRGs even after nine weekly oxaliplatin administrations that induced severe mechanical allodynia. Thus, we could not confirm previous reports that demonstrated morphological changes.12–17 We observed vacuolation of some mitochondria in peripheral nerve axons of both control and oxaliplatin-treated mice. Vacuolation may be physiological25 or may be an artifact produced during processing. Although the use of rats and different strains of mice might have contributed to the different results in other studies, oxaliplatin administration modality as discussed above may likely have caused the difference. It has been shown that peripheral neurotoxicity of oxaliplatin depended not only on the cumulative dose but also on the recovery time allowed between the doses.7,12 Recently, no axonal degeneration in peripheral nerves was demonstrated in rats with oxaliplatin-induced neuropathy that presented slowed conduction and abnormal spontaneous discharge in sensory nerves and mechanical hypersensitivity.18 Our results and previous reports taken together, it is suggested that degeneration of peripheral nerve axons is not necessary for the development of chronic neuropathic symptoms although axonal degeneration may result by chronic oxaliplatin treatment. However, IENF loss, previously reported in chemotherapy-induced neuropathy models,18,57 was also present in our model and may be involved in the generation of neuropathic symptoms.

Recently, mitochondrial dysfunction and oxidative stress have been suggested to be involved in chemotherapy-induced neuropathies.18,22–25,58,59 Oxaliplatin and paclitaxel cause functional impairment of peripheral nerve mitochondria which leads to electron leak and increased production of ROS.18,24,25 SS-31 is a mitochondria-targeted antioxidant that has been shown to be neuroprotective in a variety of disease models that involve mitochondrial dysfunction.28–34 Continuous administration of SS-31 throughout repeated administration cycles of oxaliplatin reduced both cold hypersensitivity and mechanical allodynia and also mitigated IENF loss. Furthermore, we found that acute administration of SS-31 after the onset of symptoms could only reverse cold hypersensitivity but not mechanical allodynia. Our results indicate that SS-31 can protect against the development of chronic neuropathy but cannot affect its symptom once developed. The protective effects of SS-31 are most likely via reduction of mitochondrial ROS. We showed that repeated oxaliplatin administration resulted in increased levels of ROS/RNS in DRGs and that concomitant administration of SS-31
attenuated the increase. Chronic neuropathy may involve chronic generation of mitochondrial ROS which induces neural changes that cannot be readily reversed by transient reduction of mitochondrial ROS. In contrast, SS-31 was able to alleviate cold hypersensitivity that was already present, indicating that it affected the maintenance of cold hypersensitivity. Increase in c-Fos expression after cold stimulation in mice with cold hypersensitivity was also attenuated by SS-31. The acute neuropathy may be caused directly by mitochondrial ROS, for example, mitochondrial ROS may directly affect transient receptor potential channels and/or voltage-gated sodium and potassium channels.

In summary, this murine model of oxaliplatin-induced neuropathy mimics patients' conditions and will be useful to further investigate mechanisms underlying the neuropathy and to develop drugs for its prevention and treatment. Our results suggest that mitochondrial ROS is involved differently in the acute and chronic neuropathies, and that SS-31 may be a promising candidate for prevention of oxaliplatin-induced neuropathy.

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Competing Interests

Dr. Szeto has financial interest in the subject matter and materials discussed in this article. Dr. Szeto is the inventor of the SS peptides, including SS-31, described in this article. The Cornell Research Foundation (Ithaca, New York), holds patents on this technology, and Dr. Szeto is the inventor listed on the patents (USPTO no. 7550439, USPTO no. 7576061). Dr. Szeto is the Scientific Founder of Stealth Peptides International (Newton Centre, Massachusetts), and Cornell Research Foundation has licensed the technology to Stealth Peptides International for commercial development.

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