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(54) Title: TREATMENTS FOR NEUROLOGICAL DISORDERS

(57) Abstract: Disclosed are methods of improving impaired proprioception, treating brachial plexus injuries, regenerating large and small nerve fibers, treating dorsal root nerve injuries, and improving sensory neural responses in a subject by administration of a neublastin polypeptide.



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TREATMENTS FOR NEUROLOGICAL DISORDERS

Technical Field

The invention relates to protein chemistry, molecular biology, and neurobiology.

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Background

Neublastin, also known as artemin and enovin, is a 24 kDa homodimeric, secreted protein that promotes the outgrowth and survival of neurons of the peripheral and central nervous system (Baudet et al., 2000, *Development*, 127:4335; Masure et al., 1999, *Eur. J. Biochem.*, 266:892; Rosenblad et al., 2000, *Mol. Cell Neurosci.*, 15(2):199). Neublastin mRNA is expressed predominantly in embryonic kidney and lung, and in adults, is expressed highest in pituitary gland, trachea, and placenta (Baudet et al., 2000, *Development*, 127:4335).

Neublastin is a member of the glial cell line-derived neurotrophic factor (GDNF) ligand family. GDNF ligands activate both Ras and phosphatidylinositol-3-kinase signal transduction pathways by engaging the membrane-bound c-RET receptor tyrosine kinase. This c-RET-mediated signaling requires an additional co-receptor, a glycosylphosphatidyl inositol (GPI)-anchored GDNF family receptor alpha (GFR α) protein, which confers ligand specificity to c-RET. Four GFR α co-receptor proteins have been identified (GFR α 1-4). Neublastin shows highest affinity for GFR α 3 *in vitro*, however in studies using human fibroblasts, Neublastin can stimulate c-RET-dependent signaling through either GFR α 3 or GFR α 1 (Baudet et al., 2000, *Development*, 127:4335; Masure et al., 1999, *Eur. J. Biochem.* 266:892; Rosenblad et al., 2000, *Mol. Cell Neurosci.*, 15(2):199).

Neublastin and the other GDNF family members are members of the transforming growth factor beta (TGF beta) superfamily and thus, are characterized by the presence of seven conserved cysteine residues with similar spacing which form the structure of a cysteine knot (Saarma, 1999, *Microsc. Res. Tech.*, 45:292). Each monomer contains two disulfide bonds that form a closed loop structure encircling the third disulfide to form a tight knot structure. The seventh cysteine contained within each monomer forms an

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intermolecular disulfide bond, covalently linking the monomers to form the final dimer product (Rattenholl et al 2000, *J. Mol. Biol.*, 305:523).

Summary

5 Injury of the dorsal roots results in significant and often irreversible loss of sensory functions due to apparent limited regenerative capacity of sensory axons as well as inhibitory barriers that prevent axonal entry into the spinal cord. The present invention is based, at least in part, on the surprising discovery that systemic administration of neublastin restores sensorimotor functions in animals that have undergone dorsal root
10 crush. Together with this functional recovery, systemic administration of neublastin was found to promote reentry of multiple classes of primary afferent fibers through the dorsal root entry zone (DREZ) into the spinal cord and to brainstem nuclei, resulting in reestablished synaptic function. In addition to promoting recovery from dorsal root crush injury, systemic administration of neublastin was also found to promote peripheral nerve
15 regeneration and recovery of mechanical and thermal hypersensitivity in animals that have undergone nerve crush distal to the dorsal root ganglia.

 In one aspect, the invention features a method of improving impaired proprioception by administering, to a subject that exhibits impaired proprioception, an amount of a polypeptide effective to improve proprioception in the subject, wherein the
20 polypeptide contains an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET. Also disclosed is the use of the polypeptide for the preparation of a pharmaceutical composition for improving proprioception in subject that exhibits impaired proprioception.

25 As used herein, "proprioception" refers to the ability to sense, independent of vision, the location, orientation, and movement of the body and its parts.

 In another aspect, the invention features a method of regenerating nerve fibers (e.g., dorsal root nerve fibers or nerve fibers distal to the dorsal root ganglia) by administering, to a subject that has suffered damage to or loss of nerve fibers, an amount
30 of a polypeptide effective to regenerate nerve fibers, wherein the polypeptide contains an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID

NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET. Also disclosed is the use of the polypeptide for the preparation of a pharmaceutical composition for regenerating nerve fibers in a subject that has suffered damage to or loss of nerve fibers.

5 As used herein, "regenerating nerve fibers" refers to regrowth of lost or damaged nerve fibers. The nerve fibers can be large or small nerve fibers. For example, the nerve fibers can be nerve fibers of the skin (wherein administration of the polypeptide to the subject results in skin reinnervation). The damage to or loss of nerve fibers can be the result of, e.g., a nerve crush injury or a nerve cut injury.

10 In another aspect, the invention features a method of improving an impaired sensory neural response by administering, to a subject that exhibits an impaired sensory neural response, an amount of a polypeptide effective to improve the impaired response, wherein the polypeptide contains an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, and wherein the polypeptide, when dimerized,
15 binds to a complex containing GFR α 3 and RET. Also disclosed is the use of the polypeptide for the preparation of a pharmaceutical composition for improving a sensory neural response in subject that exhibits an impaired sensory neural response.

20 The impaired sensory neural response can be characterized by, e.g., a loss of sensitivity to noxious mechanical or thermal stimuli. The impaired sensory neural response can be a result of damage to or loss of dorsal root nerve fibers or nerve fibers distal to the dorsal root ganglia.

25 In another aspect, the invention features a method of treating a brachial plexus injury by administering, to a subject that has suffered a brachial plexus injury, an effective amount of a polypeptide that contains an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET. Also disclosed is the use of the polypeptide for the preparation of a pharmaceutical composition for treating a subject with a brachial plexus injury.

30 In another aspect, the invention features a method of treating a dorsal root nerve injury by administering, to a subject that has suffered loss of synaptic function as a result of a dorsal root nerve injury, an amount of a polypeptide effective to promote reentry of

nerve fibers through the dorsal root entry zone into the spinal cord, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET. Also disclosed is the use of the polypeptide for the preparation of a pharmaceutical composition for treating a subject that has suffered a dorsal root nerve injury.

In some embodiments of the methods described herein, the polypeptide is administered to the subject within, e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 21, 28, 35, 42, 49 or 56 days following the impairment of proprioception, the damage to or loss of nerve fibers, the impairment of a sensory neural response, the brachial plexus injury, or the dorsal root nerve injury. The subject can be administered a single dose or multiple doses (e.g., 2, 3, 4, 5, 6, 7, or more doses) of the polypeptide. The polypeptide can optionally be administered to the subject intermittently (e.g., one dose per day, one dose every 2 or 3 days, or one dose per week) during a period of, e.g., 1, 2, 3, 4, or more weeks following the impairment of proprioception, the damage to or loss of nerve fibers, the impairment of a sensory neural response, the brachial plexus injury, or the dorsal root nerve injury. An "effective amount" of a polypeptide may comprise administering the polypeptide to the subject via multiple doses (e.g. two or more doses) over an extended period of time (e.g., days or weeks).

The polypeptide can optionally be administered to the subject for a limited period of time and/or in a limited number of doses following the impairment of proprioception, the damage to or loss of nerve fibers, the impairment of a sensory neural response, the brachial plexus injury, or the dorsal root nerve injury. For example, in some embodiments administration of the polypeptide to the subject can be terminated (i.e., no further administrations provided) within, e.g., one year, six months, one month, or two weeks following the impairment of proprioception, the damage to or loss of nerve fibers, the impairment of a sensory neural response, the brachial plexus injury, or the dorsal root nerve injury. In some embodiments, treatment of the subject entails administration of 50 or fewer total doses of the polypeptide (e.g., 40 or fewer doses, 30 or fewer doses, 20 or fewer doses, 15 or fewer doses, 10 or fewer doses, 9 or fewer doses, 8 or fewer

doses, 7 or fewer doses, 6 or fewer doses, 5 or fewer doses, 4 or fewer doses, 3 or fewer doses, or 2 or fewer doses).

In some embodiments of the methods described herein, the polypeptide is administered to the subject via systemic administration (e.g., via subcutaneous or
5 intravenous administration).

In some embodiments of the methods described herein, the polypeptide is administered locally to damaged neural tissue.

The subject treated according to the methods described herein can be a human or another mammal such as a mouse, rat, cow, pig, dog, cat, or monkey.

10 In another aspect, the invention features a method of regenerating nerve fibers by contacting neural tissue (e.g., dorsal root ganglia or nerve fibers distal to the dorsal root ganglia) that has suffered damage to or loss of nerve fibers with an amount of a polypeptide effective to regenerate nerve fibers, wherein the polypeptide contains an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID
15 NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET. The nerve fibers can be large or small nerve fibers. In some embodiments, the nerve fibers are nerve fibers of the skin

In some embodiments, the damage to or loss of nerve fibers is the result of a nerve crush injury. In some embodiments, the damage to or loss of nerve fibers is the
20 result of a nerve cut injury.

The neural tissue can be contacted with the polypeptide, e.g., within, e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 21, 28, 35, 42, 49 or 56 days following the damage to or loss of nerve fibers. The neural tissue can be contacted with a single dose or multiple doses (e.g., 2, 3, 4, 5, 6, 7, or more doses) of the polypeptide. The neural tissue can be
25 contacted with the polypeptide intermittently (e.g., one dose per day, one dose every 2 or 3 days, or one dose per week) during a period of, e.g., 1, 2, 3, 4, or more weeks following the damage to or loss of nerve fibers.

In some embodiments of the methods described herein, the polypeptide contains an amino acid sequence is at least 90%, 95%, or 98% identical to amino acids 15-113 of
30 SEQ ID NO:1.

In some embodiments of the methods described herein, the polypeptide contains an amino acid sequence is at least 90%, 95%, or 98% identical to SEQ ID NO:1.

In some embodiments of the methods described herein, the polypeptide contains amino acids 15-113 of SEQ ID NO:1, amino acids 15-113 of SEQ ID NO:2, amino acids
5 15-113 of SEQ ID NO:3, amino acids 15-113 of SEQ ID NO:4, amino acids 15-113 of SEQ ID NO:5, amino acids 15-113 of SEQ ID NO:8, or amino acids 15-113 of SEQ ID NO:9.

In some embodiments of the methods described herein, the polypeptide contains amino acids 10-113 of SEQ ID NO:1.

10 In some embodiments of the methods described herein, the polypeptide contains the amino acid sequence of SEQ ID NO:1, the amino acid sequence of SEQ ID NO:2, the amino acid sequence of SEQ ID NO:3, the amino acid sequence of SEQ ID NO:4, the amino acid sequence of SEQ ID NO:5, the amino acid sequence of SEQ ID NO:8, or the amino acid sequence of SEQ ID NO:9.

15 An advantage of certain treatment methods described herein is the production of persistent axonal regeneration and restoration of sensory function following a limited number of systemic injections of neublastin, thereby obviating the requirement for a long-term treatment regime (of possibly indefinite duration) and/or for spinal infusions (and its associated risks).

20 Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, the exemplary methods and materials are described below. All publications, patent
25 applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present application, including definitions, will control. The materials, methods, and examples are illustrative only and not intended to be limiting.

30 Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

Brief Description of the Drawings

Fig. 1 is an alignment of wild type human (SEQ ID NO:10), mouse (SEQ ID NO:11), and rat (SEQ ID NO:12) pre pro neublastin polypeptides. The left and right vertical lines indicate, respectively, the start of the mature 113 amino and 104 amino acid forms. The RRXR heparin binding motif is boxed.

Fig. 2 is a graph depicting the effect of systemic neublastin (artemin) administration on axonal density in the dorsal root entry zone following dorsal root crush (DRC). Asterisks indicate significant differences from vehicle-treated rats with DRC.

Fig. 3A and 3B are graphs depicting the effect of systemic neublastin (artemin) administration on response to exposure of the forepaw to hot water (Fig. 3A) and to noxious mechanical stimuli (Fig. 3B) following DRC. Arrows indicate the time when each injection of neublastin or vehicle was made. Asterisks indicate behavioral responses significantly ($p \leq 0.05$) different from baseline values obtained prior to DRC.

Fig. 3C is a graph depicting the effect of systemic neublastin (artemin) administration on licking responses, indicated by cumulative time spent licking a forepaw injected with formalin, following DRC. The asterisk indicates a significant ($p \leq 0.05$) difference in licking response relative to the group with DRC and vehicle treatment (DRC/vehicle).

Fig. 3D is a graph depicting the effect of systemic neublastin (artemin) administration on FOS expression at day 14 in ipsilateral dorsal horn in response to formalin injection into the forepaw following DRC. The sham-operated group and the group that received DRC and neublastin (artemin) treatment both demonstrated significant ($p \leq 0.05$) increases in formalin-induced FOS expression, as indicated by the asterisks.

Fig. 3E is a graph depicting the effect of systemic neublastin (artemin) administration on internalization of NK1 receptors following a noxious mechanical pinch applied to rats with carrageenan-induced inflammation that had undergone DRC. Asterisks indicate significant differences from the non-inflamed (saline-treated) groups.

Fig. 3F is a graph depicting the effect of systemic neublastin (artemin) administration on NK1 receptor internalization in lamina I/II of dorsal horn following

DRC. Asterisks indicate significant ($p \leq 0.05$) differences from the saline injected, uninflamed group.

Fig. 4 (top) are graphs depicting traces of field potentials recorded extracellularly in the ventral spinal cord in response to electrical stimulation of the median or radial nerves in the ipsilateral forelimb. On the unlesioned side of experimental animals (intact roots), the synaptic responses began 1.0 to 1.5 ms after the stimulus, with rise-times of 1.0 to 1.5 ms, both in vehicle-treated and artemin-treated animals. In artemin-treated rats, there was substantial recovery of these synaptic inputs at 1.4 and 7.5 months after DRC. There was no significant recovery of synaptic function after DRC in vehicle-treated rats, even at 7.5 months.

Fig. 4 (bottom) is a scatter plot of the maximum synaptic response to stimulation of the medial or radial nerve recorded in experimental animals. Each symbol represents the results from one animal, either after DRC or for unlesioned (intact) roots on the contralateral side of the same animal. The average maximum response for each group is shown with an open circle and vertical line (mean $\pm$ 1 S.E.). The groups tested at ~1 month included postoperative times of 0.7 to 1.4 months. All 9 animals treated with artemin showed substantial regeneration after DRC, with an average amplitude 1/4 to 1/3 that of normal responses. None of the 8 vehicle-treated rats showed any appreciable regeneration after DRC.

Figs. 5A-5D are graphs depicting the effect of systemic neublastin (artemin) administration on recovery of the following sensorimotor functions over a 42 day observation period subsequent to DRC: placement/stabilization (Fig. 5A); ability to walk along a beam over an open area (Fig. 5B); numbers of foot slips when walking across a horizontal ladder (Fig. 5C); and contact-evoked grasping (Fig. 5D). Arrows indicate each injection of neublastin (artemin) or vehicle. Asterisks indicate significant ($p \leq 0.05$) differences in behavioral parameters relative to the first measurement taken after DRC or sham surgery.

Figs. 6A-6G are graphs depicting persistent functional recovery six months after DRC in systemic neublastin (artemin) treated rats: responses to noxious thermal, mechanical and chemical stimuli (Figs. 6A-6C, respectively); and performance in placement stabilization, beam walking, horizontal ladder, and contact-evoked grasping

(Figs. 6D-6G, respectively). Asterisks indicate significant differences in behavioral responses of the neublastin-treated DRC group when compared to the vehicle-treated DRC group.

Fig. 6H is a graph depicting persistent recovery of postsynaptic FOS expression in the ipsilateral dorsal horn six months after DRC in systemic neublastin (artemin) treated rats. Asterisks indicate significant ($p \leq 0.05$) differences from the saline injected group.

Figs. 7A and 7B are graphs depicting the effect of systemic neublastin (artemin) administration on dorsal root ganglia neuronal profiles expressing N52, CGRP or P2X₃ and co-expressing either GFR α 3 (Fig. 7A) or RET (Fig. 7B) 14 days after DRC.

Figs. 8A-8D are graphs depicting the effect of systemic neublastin (artemin) administration on tactile pain responses following sham L5 spinal nerve surgery (Fig. 8A), L5 spinal nerve section (Fig. 8B), L5 spinal nerve ligation (Fig. 8C), and L5 spinal nerve crush (Fig. 8D). Arrows indicate the time when each injection of neublastin or vehicle was made.

Figs. 9A-9D are graphs depicting the effect of systemic neublastin (artemin) administration on thermal pain responses following sham L5 spinal nerve surgery (Fig. 9A), L5 spinal nerve section (Fig. 9B), L5 spinal nerve ligation (Fig. 9C), and L5 spinal nerve crush (Fig. 9D). Arrows indicate the time when each injection of neublastin or vehicle was made.

Detailed Description

The present invention provides methods of improving impaired proprioception, treating brachial plexus injuries, regenerating large and small nerve fibers, treating dorsal root nerve injuries, and improving sensory neural responses in a subject by administration of a neublastin polypeptide. As disclosed in the accompanying Examples, systemic administration of neublastin was found to restore sensory function in animals that have undergone dorsal root crush, promote reentry of nerve fibers through the DREZ into the spinal cord of injured animals, and promote peripheral nerve regeneration and recovery of mechanical and thermal hypersensitivity in animals that have undergone nerve crush distal to the dorsal root ganglia.

Neublastin Polypeptides

Mature wild type human neublastin is 113 amino acids in length and has the following amino acid sequence: AGGPGSRARAAGARGCRLRSQ LVPVRALGLGHR SDELVRFRFCSGSCRRARSPHDLSLASLLGAGALRPPPGSRPVSQPCCRPTRYEAV
 5 SFMDVNSTWRTVDRLSATA CGCLG (SEQ ID NO:1). Polypeptides having the amino acid sequence of SEQ ID NO:1 or biologically active variants of thereof can be used in the methods described herein. A variant neublastin polypeptide can contain one or more additions, substitutions, and/or deletions, as detailed in the following sections. Wild-type neublastin polypeptides and biologically active variants thereof are collectively referred
 10 to herein as “neublastin polypeptides.”

A variant neublastin polypeptide can vary in length from the corresponding wild-type polypeptide. Although the mature human neublastin polypeptide (SEQ ID NO:1) consists of the carboxy terminal 113 amino acids of pre pro neublastin (SEQ ID NO:10), not all of the 113 amino acids are required to achieve useful neublastin biological
 15 activity. Amino terminal truncation is permissible. Thus, a variant neublastin polypeptide can contain, for example, the carboxy terminal 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, or 113 amino acids of SEQ ID NO:1 (i.e., its length can be 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, or 113 amino acids).

A variant neublastin polypeptide can also vary in sequence from the corresponding wild-type polypeptide. In particular, certain amino acid substitutions can be introduced into the neublastin sequence without appreciable loss of a neublastin biological activity. In exemplary embodiments, a variant neublastin polypeptide (i) contains one or more amino acid substitutions, and (ii) is at least 70%, 80%, 85%,
 25 90%, 95%, 98% or 99% identical to SEQ ID NO:1 (or 70%, 80%, 85%, 90%, 95%, 98% or 99% identical to amino acids 15-113 of SEQ ID NO:1). A variant neublastin polypeptide differing in sequence from SEQ ID NO:1 (or differing in sequence from amino acids 15-113 of SEQ ID NO:1) may include one or more amino acid substitutions (conservative or non-conservative), one or more deletions, and/or one or more insertions.

30 Fig. 1 is an alignment of the wild type human, mouse, and rat pre pro neublastin polypeptides. The vertical lines in Fig.1 indicate the start of the mature 113 amino acid

form (left vertical line) and 104 amino acid form (right vertical line) of neublastin. The RRXR heparin binding motif is boxed. This alignment of naturally occurring, bioactive forms of neublastin indicates specific exemplary residues (i.e., those that are not conserved among the human, mouse, and rat forms) that can be substituted without eliminating bioactivity.

Percent identity between amino acid sequences can be determined using the BLAST 2.0 program. Sequence comparison can be performed using an ungapped alignment and using the default parameters (Blossom 62 matrix, gap existence cost of 11, per residue gap cost of 1, and a lambda ratio of 0.85). The mathematical algorithm used in BLAST programs is described in Altschul et al., 1997, *Nucleic Acids Research* 25:3389-3402.

A conservative substitution is the substitution of one amino acid for another with similar characteristics. Conservative substitutions include substitutions within the following groups: valine, alanine and glycine; leucine, valine, and isoleucine; aspartic acid and glutamic acid; asparagine and glutamine; serine, cysteine, and threonine; lysine and arginine; and phenylalanine and tyrosine. The non-polar hydrophobic amino acids include alanine, leucine, isoleucine, valine, proline, phenylalanine, tryptophan and methionine. The polar neutral amino acids include glycine, serine, threonine, cysteine, tyrosine, asparagine and glutamine. The positively charged (basic) amino acids include arginine, lysine and histidine. The negatively charged (acidic) amino acids include aspartic acid and glutamic acid. Any substitution of one member of the above-mentioned polar, basic or acidic groups by another member of the same group can be deemed a conservative substitution.

Non-conservative substitutions include those in which (i) a residue having an electropositive side chain (e.g., Arg, His or Lys) is substituted for, or by, an electronegative residue (e.g., Glu or Asp), (ii) a hydrophilic residue (e.g., Ser or Thr) is substituted for, or by, a hydrophobic residue (e.g., Ala, Leu, Ile, Phe or Val), (iii) a cysteine or proline is substituted for, or by, any other residue, or (iv) a residue having a bulky hydrophobic or aromatic side chain (e.g., Val, Ile, Phe or Trp) is substituted for, or by, one having a smaller side chain (e.g., Ala, Ser) or no side chain (e.g., Gly).

A biologically active variant neublastin polypeptide, when dimerized, binds to a ternary complex containing GFR α 3 and RET. Any method for detecting binding to this complex can be used to evaluate the biological activity a variant neublastin polypeptide. Exemplary assays for detecting the ternary complex-binding ability of a variant
5 neublastin polypeptide are described in WO00/01815 (the content of which is incorporated herein by reference).

A variant neublastin polypeptide can also be assessed to evaluate its ability to trigger the neublastin signaling cascade. For example, the Kinase Receptor Activation (KIRA) assay can be used to assess the ability of a variant neublastin polypeptide to
10 induce RET autophosphorylation (*See also*, Sadick et al., 1996, *Anal. Biochem.*, 235(2):207).

Substitutions at one or more of the following amino acid residues are expected to result in a variant neublastin polypeptide having reduced or absent heparin binding ability as compared to wild type neublastin: Arg 48, Arg 49, Arg 51, Ser 46, Ser 73, Gly 72, Arg
15 39, Gln 21, Ser 20, Arg 68, Arg 33, His 32, Val 94, Arg 7, Arg 9, or Arg 14. Reference to a neublastin amino acid residue by position number refers to the numbering of residues relative to SEQ ID NO:1. A neublastin amino acid residue designated for substitution (e.g., an arginine residue at position 48, 49, and/or 51) can be substituted with a non-conservative amino acid residue (e.g., glutamic acid) or a conservative or amino acid
20 residue. Exemplary amino acids that can be substituted at a residue identified herein (e.g., position 48, 49, and/or 51) include glutamic acid, aspartic acid, and alanine.

Examples of variant neublastin polypeptides that exhibit reduced or absent heparin binding are disclosed in Table 1. Amino acid residues of the variant neublastin polypeptides that are mutated as compared to the corresponding wild type position are
25 bolded and underlined. In addition, the neublastin polypeptide (113, 99, or 104 amino acids in length) used as the background for the substitution is depicted in Table 1.

Table 1: Variant Neublabin Polypeptides

SEQ ID NO	Position Substituted	Length of Polypeptide	Amino Acid Sequence
2	Arg 48	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>E</u> ARSPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG
3	Arg 49	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>E</u> ARSPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG
4	Arg 51	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>R</u> AE <u>E</u> SPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG
5	Arg 48 and Arg 49	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>E</u> <u>E</u> ARSPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG
6	Arg 48 and Arg 49	99	GCRLRSQ LVPVRA LGLGHRSEDELVRFRF CSGSC <u>E</u> <u>E</u> ARSPHDLSLASLLGAGALRPP GSRPVSQPCCRPTRYEAVSFMDVNSTW RTVDRLSATAACGCLG
7	Arg 48 and Arg 49	104	AAGARGCRLRSQ LVPVRA LGLGHRSE LVRFRFCSGSC <u>E</u> <u>E</u> ARSPHDLSLASLLGA GALRPPPGSRPVSQPCCRPTRYEAVSFM DVNSTWRTVDRLSATAACGCLG
8	Arg 49 and Arg 51	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>E</u> <u>A</u> <u>E</u> SPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG
9	Arg 48 and Arg 51	113	AGGPGSRARAAGARGCRLRSQ LVPVRA LGLGHRSEDELVRFRFCSGSC <u>E</u> <u>R</u> <u>A</u> <u>E</u> SPHD LSLASLLGAGALRPPPGSRPVSQPCCRPT RYEAVSFMDVNSTWRTVDRLSATAACGC LG

A neublastin polypeptide can be optionally coupled to a polymer (e.g., a polyalkylene glycol moiety such as a polyethylene glycol moiety). In some embodiments, the polymer is coupled to the polypeptide at a site on the neublastin polypeptide that is an N terminus. In some embodiments, a variant neublastin polypeptide includes at least one amino acid substitution with respect to SEQ ID NO:1 (or with respect to amino acids 15-113 of SEQ ID NO:1), which provides an internal polymer conjugation site to which a polymer can be conjugated. In some embodiments, the polymer is coupled to a variant neublastin polypeptide at a residue (numbered in accordance with the sequence of SEQ ID NO:1) selected from the group consisting of position 14, position 39, position 68, and position 95. Exemplary neublastin variants that provide internal polymer conjugation sites are described in WO 02/060929 and WO 04/069176 (the contents of which are incorporated herein by reference).

A polypeptide can optionally contain heterologous amino acid sequences in addition to a neublastin polypeptide. "Heterologous," as used when referring to an amino acid sequence, refers to a sequence that originates from a source foreign to the particular host cell, or, if from the same host cell, is modified from its original form. Exemplary heterologous sequences include a heterologous signal sequence (e.g., native rat albumin signal sequence, a modified rat signal sequence, or a human growth hormone signal sequence) or a sequence used for purification of a neublastin polypeptide (e.g., a histidine tag).

Neublastin polypeptides can be isolated using methods known in the art. Naturally occurring or recombinantly produced neublastin polypeptides can be isolated from cells or tissue sources using standard protein purification techniques. Alternatively, mutated neublastin polypeptides can be synthesized chemically using standard peptide synthesis techniques. The synthesis of short amino acid sequences is well established in the peptide art. *See, e.g., Stewart, et al., Solid Phase Peptide Synthesis* (2d ed., 1984).

In some embodiments, neublastin polypeptides are produced by recombinant DNA techniques. For example, a nucleic acid molecule encoding a neublastin polypeptide can be inserted into a vector, e.g., an expression vector, and the nucleic acid can be introduced into a cell. Suitable cells include, e.g., mammalian cells (such as human cells or CHO cells), fungal cells, yeast cells, insect cells, and bacterial cells (e.g.,

E. coli). When expressed in a recombinant cell, the cell is preferably cultured under conditions allowing for expression of a neublastin polypeptide. The neublastin polypeptide can be recovered from a cell suspension if desired. As used herein, "recovered" means that the mutated polypeptide is removed from those components of a cell or culture medium in which it is present prior to the recovery process. The recovery process may include one or more refolding or purification steps. Buffers and methods for inducing folding of a denatured neublastin polypeptide are described in, e.g., PCT Application Number PCT/US2005/029638.

Variant neublastin polypeptides can be constructed using any of several methods known in the art. One such method is site-directed mutagenesis, in which a specific nucleotide (or, if desired a small number of specific nucleotides) is changed in order to change a single amino acid (or, if desired, a small number of predetermined amino acid residues) in the encoded variant neublastin polypeptide. Many site-directed mutagenesis kits are commercially available. One such kit is the "Transformer Site Directed Mutagenesis Kit" sold by Clontech Laboratories (Palo Alto, CA).

Pharmaceutical Compositions

A neublastin polypeptide can be incorporated into a pharmaceutical composition containing a therapeutically effective amount of the polypeptide and one or more adjuvants, excipients, carriers, and/or diluents. Acceptable diluents, carriers and excipients typically do not adversely affect a recipient's homeostasis (e.g., electrolyte balance). Acceptable carriers include biocompatible, inert or bioabsorbable salts, buffering agents, oligo- or polysaccharides, polymers, viscosity-improving agents, preservatives and the like. One exemplary carrier is physiologic saline (0.15 M NaCl, pH 7.0 to 7.4). Another exemplary carrier is 50 mM sodium phosphate, 100 mM sodium chloride. Further details on techniques for formulation and administration of pharmaceutical compositions can be found in, e.g., REMINGTON'S PHARMACEUTICAL SCIENCES (Maack Publishing Co., Easton, Pa.).

Administration of a pharmaceutical composition containing a neublastin polypeptide can be systemic or local. Pharmaceutical compositions can be formulated such that they are suitable for parenteral and/or non-parenteral administration. Specific

administration modalities include subcutaneous, intravenous, intramuscular, intraperitoneal, transdermal, intrathecal, oral, rectal, buccal, topical, nasal, ophthalmic, intra-articular, intra-arterial, sub-arachnoid, bronchial, lymphatic, vaginal, and intra-uterine administration. Administration can be to the peripheral nervous system and/or the central nervous system (CNS).

Administration may be by periodic injections of a bolus of the pharmaceutical composition or may be made more continuous by intravenous or intraperitoneal administration from a reservoir which is external (e.g., an IV bag) or internal (e.g., a bioerodable implant, a bioartificial organ, or a colony of implanted neublastin production cells). See, e.g., U.S. Pat. Nos. 4,407,957, 5,798,113, and 5,800,828, each incorporated herein by reference.

In particular, administration of a pharmaceutical composition may be achieved using suitable delivery means such as: a pump (see, e.g., *Annals of Pharmacotherapy*, 27:912 (1993); *Cancer*, 41:1270 (1993); *Cancer Research*, 44:1698 (1984), incorporated herein by reference); microencapsulation (see, e.g., U.S. Pat. Nos. 4,352,883; 4,353,888; and 5,084,350, herein incorporated by reference); continuous release polymer implants (see, e.g., Sabel, U.S. Pat. No. 4,883,666, incorporated herein by reference); macroencapsulation (see, e.g., U.S. Pat. Nos. 5,284,761, 5,158,881, 4,976,859 and 4,968,733 and published PCT patent applications WO92/19195, WO 95/05452, each incorporated herein by reference); naked or unencapsulated cell grafts to the CNS (see, e.g., U.S. Pat. Nos. 5,082,670 and 5,618,531, each incorporated herein by reference); injection, either subcutaneously, intravenously, intra-arterially, intramuscularly, or to other suitable site; or oral administration, in capsule, liquid, tablet, pill, or prolonged release formulation.

In one embodiment, a pharmaceutical composition is delivered directly into the CNS (e.g., the brain ventricles, brain parenchyma, or the intrathecal space). The pharmaceutical composition can be delivered intrathecally.

Examples of parenteral delivery systems include ethylene-vinyl acetate copolymer particles, osmotic pumps, implantable infusion systems, pump delivery, encapsulated cell delivery, liposomal delivery, needle-delivered injection, needle-less injection, nebulizer, aerosolizer, electroporation, and transdermal patch.

A pharmaceutical composition containing a neublastin polypeptide can optionally be administered to a subject within a specified period of time following damage or injury to nerve tissue (e.g., a dorsal root crush or a crush of a nerve distal to the dorsal root ganglia). For example, the pharmaceutical composition can be administered to the
5 subject within, e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 21, 28, 35, 42, 49 or 56 days following damage or injury. The subject can be administered a single dose or multiple doses (e.g., 2, 3, 4, 5, 6, 7, or more doses) of the pharmaceutical composition. Administrations of multiple doses can be separated by intervals of hours, days, weeks, or months.

10 Formulations suitable for parenteral administration conveniently contain a sterile aqueous preparation of the neublastin polypeptide, which preferably is isotonic with the blood of the recipient (e.g., physiological saline solution). Formulations may be presented in unit-dose or multi-dose form.

An exemplary formulation contains a neublastin polypeptide described herein and
15 the following buffer components: sodium succinate (e.g., 10 mM); NaCl (e.g., 75 mM); and L-arginine (e.g., 100 mM).

Formulations suitable for oral administration may be presented as discrete units such as capsules, cachets, tablets, or lozenges, each containing a predetermined amount of the neublastin polypeptide; or a suspension in an aqueous liquor or a non-aqueous
20 liquid, such as a syrup, an elixir, an emulsion, or a draught.

Therapeutically effective amounts of a pharmaceutical composition may be administered to a subject in need thereof in a dosage regimen ascertainable by one of skill in the art. For example, a composition can be administered to the subject, e.g., systemically at a dosage from 0.01 µg/kg to 1000 µg/kg body weight of the subject, per
25 dose. In another example, the dosage is from 1 µg/kg to 100 µg/kg body weight of the subject, per dose. In another example, the dosage is from 1 µg/kg to 30 µg/kg body weight of the subject, per dose, e.g., from 3 µg/kg to 10 µg/kg body weight of the subject, per dose.

In order to optimize therapeutic efficacy, a neublastin polypeptide is first
30 administered at different dosing regimens. The unit dose and regimen depend on factors that include, e.g., the species of mammal, its immune status, the body weight of the

mammal. Typically, protein levels in tissue are monitored using appropriate screening assays as part of a clinical testing procedure, *e.g.*, to determine the efficacy of a given treatment regimen.

The frequency of dosing for a neublastin polypeptide is within the skills and clinical judgement of physicians. Typically, the administration regime is established by clinical trials which may establish optimal administration parameters. However, the practitioner may vary such administration regimes according to the subject's age, health, weight, sex and medical status. The frequency of dosing may be varied depending on whether the treatment is prophylactic or therapeutic.

Methods of Treatment

The neublastin polypeptides described herein can be used for treating impaired proprioception, treating brachial plexus injuries, regenerating large and small nerve fibers, promoting reentry of nerve fibers through the DREZ into the spinal cord, and/or improving sensory neural responses.

1. Treatment of Impaired Proprioception

The neublastin polypeptides disclosed herein (and pharmaceutical compositions comprising same) can be used in methods for treating impaired proprioception.

Impaired proprioception inhibits properly coordinated muscular effort and results in an altered perception of body-space relation. In humans, loss of proprioception often occurs as a result of nerve trauma or damage (*e.g.*, damage resulting from an injury). Injuries that can be associated with subsequent loss or impairment of proprioception include, *e.g.*, stroke-related nerve damage or other ischemia-related neural injury, surgery, whiplash, concussions, cervical myelopathy (*e.g.*, due to cervical stenosis), and injuries related to scoliosis (*e.g.*, idiopathic scoliosis). Impairment can also result from complications due to diabetes or cancer (*e.g.*, inflammation or injury due to an invasive tumor) or can result from tissue injury resulting from exposure to cytotoxic factors such as chemotherapy. Homeostatic proprioception can be impaired following use of peripheral or central nerve blocks, for example, during a surgical procedure.

Loss or impairment of proprioception can also occur from conditions not involving direct tissue damage or injury. Patients who suffer from, for example, joint hypermobility or Ehlers-Danlos Syndrome (a genetic condition that results in weak connective tissue throughout the body) can present with impaired proprioception.

5 Proprioception can also be temporarily or permanently impaired from certain viral infections. In some cases, temporary loss or impairment of proprioception may happen periodically during growth such as growth during adolescence. Other types of growth that could affect proprioception in a patient include, e.g., large gains or reductions in bodyweight/size due to fluctuations of fat and muscle content. Proprioceptive loss can
10 also present in subjects who gain new levels of flexibility, stretching, and contortion, for example, a limb experiencing a new range of motion after a prolonged immobilization. In rare cases, temporary impairment of proprioception has also been known to occur following an overdose of vitamin B6 (pyridoxine and pyridoxamine).

Loss or impairment of proprioception can affect the upper extremities, lower
15 extremities, or both, depending on the location and/or nature of the causative injury or condition. For example, an injury to the lower spine may only affect proprioception from the torso downward, whereas an injury to the upper portions of the spine can result in impaired proprioception in both upper and lower extremities.

Following administration of neublastin to a subject (e.g., a human), the efficacy
20 (improvement) of the treatment on impaired proprioception can be assessed by comparing the subject's proprioception before and after treatment. Post-treatment assessment can occur immediately or shortly after treatment (e.g., 6, 12, 18, or 24 hours after treatment) and/or can occur days, weeks, or months following treatment. Where progression of the improvement of impaired proprioception following one or more
25 neublastin treatments is to be assessed, a subject's proprioception can be evaluated or measured at multiple time points following neublastin treatment (e.g., a one day, two day, and one week evaluation; a one week, one month, and six month evaluation; a one month, six month, and one year evaluation).

Suitable methods of evaluating or measuring proprioception in a subject are
30 known in the art. Where upper extremity proprioception is evaluated, examples of such evaluation methods include detection of joint motion (e.g., Cook et al. (1986) Clin.

Orthop. Relat. Res. 213:118-24) and passive position matching tests using devices described in, e.g., Swanik et al. (1996) J Athl Train. 31(2):119-24 and Ulkar et al. (2004) Br. J. Sports Med. 38:549-52. In addition, upper extremity deficits in proprioception can be tested in humans using, e.g., the field sobriety test, wherein a subject attempts to touch the nose with the eyes closed. Subjects with normal proprioception generally make errors of no more than 2 cm. Subjects with severely impaired proprioception cannot perceive the location of their hands (or noses) without looking.

Where lower extremity proprioception is evaluated (e.g., hip or knee proprioception), proprioception can be assessed following a test for patient joint-position sense (Takayama et al. (2005) Spine 30(1):83-86) or measured using a manual protractor or electrogoniometer (Mendelsohn et al. (2004) Am. J. Phys. Med. Rehabil. 83(8):624-32). Lower extremity deficits in proprioception can also be determined by measuring static and dynamic balance. Proprioception of the spine can also be measured. Examples of such methods and devices are described in Christensen (1999) J Manipulative Physiol. Ther. 22(1):10-14 and U.S. Patent No. 6,969,360.

The measurement or evaluation of proprioception in a patient can be quantitative or generally qualitative, e.g., a survey given to a patient where he or she rates the severity or extent of an altered perception as described in Klein et al. (2003) Reg. Anesth. Pain Med. 28(5):433-38. Additional proprioception tests are described in, e.g., Lee et al. (2003) Clin. Biomech. 18(9):843-47 and al-Othman et al. (1998) Orthopedics 21(6):677-79.

The Examples contained herein describe several assays useful for measuring proprioception in non-human model systems. Animal models of impaired proprioception are generally injury-related impaired proprioception models. Injuries can include, for example, unilateral C4-T2 dorsal root crush (Ramer et al. (2000) Nature 403:312-316). Additional suitable animal models of proprioception are described, for example, in Gaviria et al. (2002) J. Neurotrauma 19(2):205-221.

2. Treatment of Brachial Plexus Injuries

As described in the Examples, administration of neublastin to a mammal can result in restoration of sensorimotor function following nerve injuries to the brachial

plexus. Brachial plexus injuries are caused by damage (injury) to the brachial plexus, a network of peripheral nerves (the C5, C6, C7, C8 and T1 nerves, in humans) that travel from the spine to the shoulder, arm, and hand. Symptoms of brachial plexus injuries can include a limp or paralyzed arm, lack of muscle control in the arm, hand, or wrist, and
5 lack of feeling or sensation in the arm or hand. The neublastin polypeptides disclosed herein (and pharmaceutical compositions comprising same) can be used in methods of treating brachial plexus injuries in a subject (e.g., a human).

Brachial plexus nerves can be stretched, avulsed, or ruptured due to large amounts of stress put on the neck. Adults may suffer brachial plexus injuries through severe
10 physical trauma such as an automobile or motorcycle accident (e.g., following a whiplash injury). Many brachial plexus injuries occur *in utero* or at birth when a baby's shoulders become impacted causing the brachial plexus nerves to stretch or tear.

There are four types of brachial plexus injuries: (i) neuropraxia (stretch), in which the nerve has been damaged but not torn; (ii) avulsion, in which the nerve is torn from the
15 spine; (iii) rupture, in which the nerve is torn but not at the spinal attachment; and (iv) neuroma, in which the nerve has attempted to heal itself but scar tissue has grown around the injury, placing pressure on the injured nerve and preventing the nerve from conducting signals to the muscles. Neuropraxia is the most common type of brachial plexus injury and can result in permanent and severe impairment of sensory function
20 within the shoulder, arm, and hand.

Following administration of neublastin to a subject (e.g., a human), the efficacy (improvement) of the treatment on the brachial plexus injury can be assessed by comparing the extent or severity of a subject's injury before and after treatment. The efficacy of neublastin treatment on a brachial plexus injury can be assessed as a
25 monotherapy or as part of a multi-therapeutic regimen. For example, neublastin can be administered in conjunction with other clinically relevant treatments for brachial plexus injury including, neurolysis (to remove scar tissue), muscle transfer, nerve grafts, or nerve reconstructive surgery.

Multiple modalities can be used to assess the extent or severity of a brachial
30 plexus injury, including clinical examination, electrodiagnostic studies (e.g., electromyography (EMG), nerve conduction velocity (NCV), sensory nerve action

potential (SNAP), and somatosensory evoked potential (SSEP)) and imaging studies (e.g., Computed Tomography (CT) Image Scan, Magnetic Resonance Imaging (MRI)) (Harper (2005) *Hand. Clin.* 21(1):39-46). These modalities can be used alone or in combination, the combination often delineating specific elements of the brachial plexus that have been injured and more detailed information about the severity of the injury. Clinical examination can include, but is not limited to, qualitative motor function evaluations that score both individual muscle groups (using the five-point British Research Council Grading System) and semi-quantitative or quantitative methods such as functional muscle group activities, including abduction, external rotation, and hand-to-head, hand-to-back and hand-to-mouth movements as well as sensory and reflex exams. Examples of sensory exams include, for example, The Thermal Threshold Testing System (Somedic, Stockholm, Sweden) described in Anand et al. (2002) *Brain* 125:113-22.

The unilateral C4-T2 dorsal root crush (as described in Ramer et al. (2000) *Nature* 403:312-16) damages nerves of the brachial plexus and is a useful rat model system for studying brachial plexus injury. Additional suitable animal models of brachial plexus injury are also described in, e.g., Quintao et al. (2006) *Neuropharmacology* 50(5):624-20; Rodrigues-Filho et al. (2003) *Brain Res.* 982(2):186-94; and Rodrigues-Filho et al. (2004) *Brain Res.* 1018(2):159-70. Methods used to evaluate the efficacy of a treatment (e.g., administering to a subject a neublastin polypeptide) on a brachial plexus injury are similar to those described for human patients and include, e.g., evaluating changes in temperature threshold or changes in nerve potential.

3. Regeneration of Large and Small Nerve Fibers and Promoting Reentry of Nerve Fibers Through the DREZ into the Spinal Cord

As detailed in the Examples, systemic administration of neublastin was found to promote regeneration of nerve fibers, including axonal regeneration crossing the DREZ into the spinal cord as well as regeneration of injured nerve fibers distal to the dorsal root ganglia (DRG). Thus, the neublastin polypeptides disclosed herein (and pharmaceutical compositions containing same) can be useful in methods for regenerating, lost, damaged, or injured large (e.g., large myelinated or unmyelinated) and/or small (e.g., small

myelinated or unmyelinated) fibers of the nervous system. Administration of a neublastin polypeptide can be useful for regenerating large and small fibers of the central nervous system (e.g., brain or spinal cord) as well as the peripheral nervous system (e.g., nerves of limbs, phalanges, face, skin, or tongue).

5 Types of nerve damage that can benefit from long and/or small nerve fiber regeneration and can be treated by administration of a neublastin polypeptide generally include instances where one or more nerves are injured (e.g., crushed) or severed. The nerve damage can occur as a result of a nerve-damaging infection (e.g., a bacterial or viral meningitis, bacterial, viral, or protozoal encephalitis, or polio) or diseases

10 (e.g., hereditary, sporadic, or ideopathic diseases) such as multiple sclerosis, Gillain Barre syndrome, diabetes, Charcot-Marie-Tooth disease, Friedrich's ataxia, Bell's palsy, or spina bifida. Nerve injuries that can benefit from administration of neublastin also include those resulting from fractures, strains, or breakages of bones (or tendons or ligaments), electrical shock, exposure to certain toxic chemicals (e.g., solvents, heavy

15 metals, or nitrous oxide), certain types of burns, skin or other tissue grafting, acute compression (e.g., nerve entrapment such as ulner nerve entrapment or carpal tunnel syndrome), or nerve damage resulting from surgery other medical procedures (e.g., lingual nerve injury following tooth extraction). Additional nerve damage that can be treated using any of the neublastin compositions described herein includes damage

20 occurring as a result of, e.g., Parkinson's disease, amyotrophic lateral sclerosis, or nerve-damaging injury or inflammation associated with Alzheimer's disease or other tauopathies, subacute-sclerosing panencephalitis, progressive multifocal leuco-encephalopathy, or any of the prion-type spongioform encephalopathies.

 Following administration of neublastin to a subject (e.g., a human), the efficacy of

25 the treatment in promoting nerve regeneration can be assessed by comparing the state or function of the subject's nerve(s) before and after treatment. The efficacy of neublastin treatment on nerve regeneration can be assessed as a monotherapy or as part of a multi-therapeutic regimen. For example, neublastin can be administered in conjunction with other clinically relevant treatments for nerve regeneration including, but not limited to,

30 physical therapy, hyperbaric treatments, light-activated nerve regeneration (laser or light emitting diode), or medicaments such as methylprednisolone.

The regeneration of large or small nerve fibers can be assessed in a subject (e.g., a human) by direct analysis of one or more nerves using, for example, nerve conduction velocity recordings, the Pressure-Specified Sensory Device™ (Sensory Management Services, LLC, Baltimore MD), or imaging techniques such as those described above. In some cases, for example where regeneration is of the central nervous system, nerve regeneration can be evaluated as an increase in white matter volume (e.g., nerve mass of the spine or brain), particularly where the damage or disorder has resulted in nerve atrophy, using, e.g., magnetic resonance spectroscopy scans. Peripheral nerve regeneration can be directly assessed by biopsy and/or *ex vivo* electrophysiological techniques as described in, e.g., Polydefkis et al. (2004) Brain 127(7):1606-15.

Where nerves of the skin have been damaged (e.g., damage from a cutaneous burn or severed nerves of grafted skin), the regeneration of nerves of the skin (e.g., nerve reinnervation) following administration of a neublastin polypeptide can be assessed using a variety of methods known in the art. For example, one or more sensory functions (e.g., sensitivity of the skin) can be measured using sensory nerve action potential (SNAP) measurements or sympathetic skin response (SSR) tests as described in , e.g., Beneke et al. (1980) J Neurol. 223(4):231-39, Jazayeri et al. (2003) Electromyogr. Clin. Neurophysiol. 43(5):277-79, Huang et al. (2004) Chin. Med. J (Engl) 117(9):1317-20, or Pan et al. (2006) Arch. Phys. Med. Rehabil. 87(9):1201-06. Skin reinnervation following administration of neublastin can also be assessed in a patient by monitoring a change in responsiveness to mechanical or heat stimuli or to sympathetic reflex provocation tests, such as those described in Schmelz et al. (1998) J Neurophysiol. 79(4):1653-1660.

Alternatively (or in addition), nerve regeneration can be measured “functionally,” e.g., by measuring an improvement of impaired proprioception through regeneration of the injured nerve. Assessment methodologies for nerve regeneration can also include any of the evaluation methods for any of the nerve-related injuries described herein.

The Examples describe animal models useful for studying the effect of a neublastin treatment on nerve regeneration. The efficacy of such treatment in animal models can be evaluated by direct analysis of the nerves, for example, by immunohistochemistry techniques on a biopsy or tissue section. Alternatively, nerve

regeneration can be detected as restoration of sensation or motor activity following regeneration of the nerves. Additional animal models for studying the effects of a treatment on nerve regeneration include, for example, those described in Oudega et al. (1996) 140(2):218-29, Frykman et al. (1998) Orthop. Clin. North. Am. 19(1):209-19, Zhang et al. (2005) Adv. Biochem. Eng. Biotechnol. 94:67-89, and Pan et al. (2003) J. Neurosci. 23(36):11479-88.

4. Improvement of Sensory Neural Responses

As described in the Examples, administration of neublastin to a mammal with a nerve injury results in restoration of lost sensory-neural responses and sensorimotor functions. Thus, administration to a subject (e.g., a human) of a neublastin polypeptide described herein can be useful in restoring sensation and/or sensorimotor functions in the subject. Such sensory-neural responses can include, for example, response to sensation of pressure, temperature, and vibration (see Toibana et al. (2000) Industrial Health 38:366-371). Sensorimotor functions control, e.g., balance, equilibrium, and coordination (e.g., coordination of limb motion).

Loss of sensory-neural responses/sensorimotor function can result from damage or trauma to one or more nerves, the causes of nerve damage or trauma including any of those described herein. For example, loss or impairment of a sensory response can result from complications due to diabetes or from desensitization following exposure to extreme heat (e.g., a burn). Following administration of neublastin to a subject, the efficacy of the treatment in improving sensory neural responses can be assessed by comparing the subject's sensory nerve response(s) before and after treatment. The efficacy of neublastin treatment in improving sensory neural responses can be assessed as a monotherapy or as part of a multi-therapeutic regimen as described above. For example, neublastin can be administered in conjunction with other clinically relevant treatments for improving sensory neural responses, or in conjunction with any other treatment modality described herein (e.g., a treatment for the nerve damage or injury).

Methods of assessing an improved sensory-neural response in a human subject following treatment are numerous and include, e.g., electromyographic nerve conduction (EMG-NCV) tests and sensory nerve perception threshold testing (also referred to as

current perception threshold testing), which involves quantification of a sensory threshold to transcutaneous electrical stimulation (the minimal amount of transcutaneous electrical stimulation required to evoke a sensation in a subject). Additional methods of assessing sensorimotor function in a human subject include, for example, pinch and grip strength
5 (Dellon et al. (1997) *Ann Plat. Surg.* 38(5):493-502), angle reproduction tests (see above), threshold-to-motion tests, isometric strength testing, Romberg's Test, flexion reflexes (Hornby et al. (2003) *J Neurophysiol.* 89(1):416-26), and tests for hand-eye coordination.

Touch sensation can be assessed, for example, by gently rubbing a ball of cotton
10 on the surface of the skin of the region tested, or gently applying pressure to various locations of the region. These types of sensory nerve perception threshold assessments are useful in evaluating a wide range of clinical conditions including central and peripheral neuropathies and detection of carpal tunnel syndrome, and can involve the use of devices such as the Neurometer Current Perception Threshold (Neurotron, Inc.,
15 Baltimore, MD) or the Medi-Dx 7000 (Vax-D Medical Group, Tucson, AZ). Additional descriptions of clinical tests and devices useful for assessing sensory neural responses can be found, e.g., in Shy et al. (2003) *Neurol.* 60:898-904 and Siao et al. (2003) *Phys. Med. Rehabil. Clin. N. Am.* 14(2):261-86. Methods of assessing sensory-neural or touch-sensation responses also include sensory nerve action potential (SNAP) measurements,
20 sympathetic skin response (SSR) tests, and responsiveness to mechanical or heat stimuli or to sympathetic reflex provocation tests, such as those described above.

The Examples describe animal models for studying the effect of a treatment on improving sensory-neural responses/sensorimotor function. For example, following a nerve injury (e.g., a dorsal root crush or a crush of a nerve distal to the dorsal root
25 ganglia), sensorimotor function in an animal can be evaluated with and without treatment (i.e., treatment with a neublastin polypeptide) by assessing an animal's performance in the stabilization maneuver. Additional animal models useful in measuring sensory-neural responses and/or sensorimotor function are described in, e.g., Diamond et al. (1992) *J. Neurosci.* 12(4):1467-76, Brown et al. (2005) *J. Neurotrauma* 22(5):559-74, and
30 Magnuson et al. (2005) *J. Neurotrauma* 22(5):529-43.

The following are examples of the practice of the invention. They are not to be construed as limiting the scope of the invention in any way.

Examples

5

Example 1: Materials and Methods

Animal Surgery, Neublazin Administration, and Tracing Studies

Unilateral C4-T2 dorsal root crush (Ramer et al. (2000) Nature 403:312-16) was performed on male Sprague-Dawley rats (Harlan, Indianapolis, IN), weighing 175-250 grams. Sham surgery was processed under the same procedures without root injury. Rat neublazin (Gardell et al. (2003) Nat Med 9:1383-89) or saline vehicle was given subcutaneously on a Monday, Wednesday, and Friday schedule immediately after surgery for a total of 6 injections over 2 weeks. For transganglionic tracing, the median nerve branch of the brachial plexus was exposed under sterile conditions and a 5 µl solution of 0.5% CTB (Cholera Toxin B subunit, low salt; List Labs) was pressure injected into the nerve with multiple injection sites at 5-7 days before sacrifice.

Behavioral Observations

Behavioral assays for quantification of restoration of nociceptive, sensorimotor, and proprioceptive functions were performed according to the behavioral protocols described in Ramer et al. (2002) Mol Cell Neurosci 19:239-49 and Ramer et al. (2000) Nature 403:312-16. Paw withdrawal latency to noxious thermal stimulation was measured with a 49°C water-bath, that is, the forepaw ipsilateral to injury was immersed in a 49°C water-bath until the rat withdrew its paw or until the cut-off time of 20 seconds was reached. Ipsilateral forepaw withdrawal to noxious mechanical stimulation was tested with a Randall-Setlitz noxious pinch device (Ugo-Basil) with the cutoff set at 250 grams. Scoring of rat performance in contact-evoked grasping, beam walking, horizontal ladder and stabilization placement was done as previously described (Ramer et al. (2002) Mol Cell Neurosci 19:239-49; and Ramer et al. (2000) Nature 403:312-16).

Immunohistochemistry

Rats were transcardially perfused with 10% buffered formalin (Sigma) and cervical spinal cord, DRG, and brainstems were removed, cryoprotected (in 20% sucrose), frozen, and sectioned (10 μ m for DRG, 20 μ m for spinal cord) on a cryostat.

5 Sections were incubated with primary antibodies for CGRP (host rabbit/guinea pig, 1:10,000, Peninsula), P2X₃ (host rabbit/guinea pig, 1:10,000, Neuromics), NF200 (host mouse, 1:5,000, N52, Sigma), GFR α 3 (R11, 2 μ g/ml; Orozco et al. (2001) Eur J Neurosci 13:2177-82), Ret (2 μ g/ml; Orozco et al. (2001) Eur J Neurosci 13:2177-82), GFAP (host mouse, 1:5,000, Sigma), ED1 (host mouse, 1:2,000, Serotec), FOS (host

10 rabbit, 1:5,000, Calbiochem), CTB (host goat, 1:5,000, List Labs) and to NK1R (host rabbit, 1:5,000; Honore et al. (1999) J. Neurosci. 19:7670-78). Secondary antibodies were Cy3-conjugated goat antibody to rabbit IgG (1:1,000, Jackson), Alex fluor 488/594-conjugated goat antibodies to rabbit, mouse, or guinea pig IgG (1:1,000, Molecular Probes), and Alex fluor 594-conjugated donkey antibody to goat IgG (1:1,000, Molecular

15 Probes). Immunoreactive cells and total cells (visualized with DAPI or ethidium bromide; Guo et al. (1999) Eur. J. Neurosci. 11:946-58) were counted on randomly selected sections. Quantitative analysis of axon density within the dorsal root along the central side of DREZ, as well as the density of immunoreactivity within spinal dorsal horn, was carried out as previously described (Ramer et al. (2000) Nature 403:312-16;

20 and Wang et al. (2003) Neuroscience 121:815-24).

Nociceptive Reaction and FOS Expression in Formalin-Induced Inflammation

The experiments were performed in awake, freely moving rats as described previously (Presley et al. (1990) J Neurosci 10:323-35). The plantar surface of the

25 ipsilateral forepaw of the rat that received dorsal root crush and neublastin/vehicle treatment was injected with 100 μ l of 10% formalin subcutaneously, and the licking time on the injection site was recorded as previously described (Abbadie et al. (1992) Brain Res 578:17-25). Three hours after the injections, the rats were perfused, and C4-T2 spinal cord was harvested for immunohistochemistry to examine formalin induced FOS

30 expression in the spinal dorsal horn. The control rats received the same amount of saline injections.

Mechanical Stimulation and NK1R Internalization in Carrageenan-Induced Inflammation

The experiment was performed by the modified method described by Mantyh and colleagues (Honore et al. J. Neurosci. 19:7670-78). A subcutaneous injection of 100 μ l of a suspension of 2% λ -carrageenan (Sigma-Aldrich, St. Louis, MO) in saline (pH 6.8) was administered into the plantar surface of the forepaw of the rat. After 3 hours, the rats were subjected to non-noxious mechanical stimulation by light stroking of the dorsal forepaw every second for 5 minutes with the wooden handle of a brush or to a noxious mechanical stimulation applied as a 30 second pinch with a hemostat applied to the distal part of the forepaw. The anesthetized rats were perfused for 15 minutes with phosphate-buffered saline followed by glutaraldehyde fixative for preparation for immunohistochemical visualization of internalization of the NK1 receptor in the spinal dorsal horn.

Electrophysiological Methods

Animals were maintained at surgical levels of isoflurane anesthesia for the duration of all terminal electrophysiology experiments. Experimenters were blinded as to treatment until all experiments in the set had been completed. The cervical cord was exposed from C4 to C8 and stabilized with spinal clamps on C2 and T2. Radial, median, and/or ulnar nerves were exposed just below the brachial plexus in both forelimbs and suspended on silver hooks for stimulation. Mineral oil was applied to keep the nerves and cord from drying out. A low-impedance metal microelectrode with a large 1 mm tip exposure (A-M Systems #563410) was vertically positioned 1 mm lateral to the cord midline and manually advanced to a depth approximately 0.5 mm from the ventral boundary (i.e., in the ventral horn). A second electrode was positioned in nearby muscles surrounding the cord and recordings were made differentially. A data acquisition board (National Instruments, PCI-6036E) triggered an electrical pulse-stimulator (A-M Systems Model 2100), which delivered single 50 ms monophasic square wave pulses of 0-8V amplitude at rates from 1-11 Hz to the peripheral nerves. Unless otherwise noted, the radial nerve was stimulated using pulses with amplitude of 4V delivered at an average rate of 2 Hz. Single responses were filtered (0.1 Hz-3 kHz), digitized (16 bits, 20kHz

sampling rate), averaged (typically, 50 traces) and stored for analysis off-line. The spinal preparation usually produced stable, replicable neuronal potentials for several hours. Recordings were made from the ventral horn at each segmental level (C4-C8) on both sides of the cord in response to ipsilateral stimulation of individual brachial nerves.

- 5 Averaged cervical ventral root potentials in normal, unlesioned rats typically ranged from 100-300 μ V in maximum amplitude (noise level typically $\sim$ 10 μ V), depending upon the individual animal, the nerve stimulated, and the rostrocaudal location of the recording electrode. The peak magnitude of the ventral horn field potential at 2-6 ms latency was adopted as a robust physiological measure of the summed short latency monosynaptic
- 10 response in the cord at a given location. A further refinement of the estimation of monosynaptic response fits a standard model trace to a given response curve (Mears et al. (1994) Exp. Neurol. 130:115-19). The model trace has latency and exponential decay characteristics typical of excitatory post-synaptic currents generated by Ia-motoneuron synapses. The peak value of the fitted curve, usually very close to the raw peak
- 15 magnitude, was then adopted as the estimate of the summed population monosynaptic response for stimulation of that segmental level and peripheral nerve. The maximum response observed amongst all recording sites was taken as the global estimate of synaptic function. This maximum response was deemed significantly larger than zero if its value was greater than 3 times the noise level, typically $\sim$ 30 μ V. To rule out possible
- 20 false negative responses due to decline in the physiological state of the spinal cord, recordings were made first on the lesioned side of the cord and then on the unlesioned side, where the existence of normal responses ensured that the spinal cord was still functionally uncompromised.

25 Statistical Analysis

Statistical comparisons between treatment groups were done using ANOVA followed by Fisher Least Significant Difference test. Pairwise comparisons were made with Student t-test. Significance was set at $P = 0.05$.

Example 2: Neublastin Promotes Axonal Regeneration into the Spinal Cord

N52, CGRP and P2X₃ immunolabelling was employed to visualize myelinated, unmyelinated peptidergic and unmyelinated "peptide-poor" fibers, respectively (Ramer et al. (2000) Nature 403:312-16). Together, these markers label nearly all DRG neurons (Bradbury et al. (1998) Mol. Cell. Neurosci. 12:256-68; Averill et al. (1995) Eur. J. Neurosci. 7:1484-94; and Bennett et al. (1998) J. Neurosci. 18:3059-72). Neublastin (1 mg/kg, subcutaneous administration) given on a Monday-Wednesday-Friday schedule for two consecutive weeks starting on the day of dorsal root crush (DRC) injury of the brachial plexus (the schedule used for Examples 2-8) elicited re-growth of both myelinated and unmyelinated axons through the DREZ. Sections from sham-operated animals showed uninterrupted immunofluorescent labeling for N52, CGRP and P2X₃ in axons from the periphery through the DREZ. Labeling for these markers terminated abruptly at the DREZ in DRC vehicle-treated rats. In contrast, sections from DRC neublastin-treated rats showed all the immunohistochemical markers central to the DREZ. Neublastin normalized DRC-induced reductions in immunolabeled axon densities (Fig. 2; Ramer et al. (2000) Nature 403:312-16). Moreover, in neublastin DRC tissues, immunofluorescence for CGRP and P2X₃ was found principally in the outer laminae of the dorsal horn whereas that for CTB was distributed throughout the outer and intermediate laminae, corresponding to the normal termination patterns of these fibers. Neublastin had no detectable effects in sham-operated animals.

Example 3: Systemic Neublastin Restores Nociceptive Functions

Withdrawal response to immersion of the forepaw ipsilateral to DRC or sham surgery in a 49°C water bath or to noxious pressure was recorded. Animals with DRC injury and treated with vehicle showed marked insensitivity to both noxious heat or pressure with little change in responses throughout the 6 week evaluation (Figs. 3A and 3B) and at 6 months after DRC (Figs. 6A and 6B). Neublastin caused a progressive and rapid recovery of both thermal and mechanical thresholds in DRC rats. Responses to noxious stimuli were present within 4 days, and approached normal levels within 7 days of DRC (Figs. 3A and 3B). Termination of neublastin treatment on day 11 did not affect restoration of nociceptive responses since they remained fully normalized over the entire

42 day observation period and also at the 6 month time-point (Figs. 6A and 6B). Neublazin did not alter response thresholds in sham-operated groups at any time-point (Figs. 3A and 3B and Figs. 6A and 6B).

5 Example 4: Systemic Neublazin Restores Post-Synaptic Functions

Noxious stimulus-induced expression of the proto-oncogene product FOS in the spinal dorsal horn is indicative of neuronal excitation of post-synaptic cells (Presley et al. (1990) J Neurosci 10:323-35; Hunt et al. (1987) Nature 328:632-34; and Harris (1998) Brain Res Bull 45:1-8). Forepaw formalin injection produced stereotypic licking
10 behaviors along with increased numbers of FOS-positive spinal cord cell profiles (Figs. 3C and 3D). DRC injury with vehicle treatment abolished both formalin-induced licking and evoked spinal FOS (Figs. 3C and 3D). In contrast, neublazin preserved both the formalin-evoked behavioral and FOS responses at the day 14 (Figs. 3C and 3D) and 6 month time points (Fig. 6C).

15 Evoked internalization of the NK1 receptor in the spinal dorsal horn by either noxious mechanical or by innocuous tactile stimuli in injured animals is indicative of post-synaptic responsiveness of dorsal horn neurons to substance P released from primary afferent fibers (Honore et al. J. Neurosci. 19:7670-78). Noxious pinch elicited internalization of the NK1 receptor in 96 ± 2.6 % of NK1-R positive dorsal horn profiles
20 (Fig. 3E) and light brush following carrageenan injection caused internalization in 62 ± 4.7 % of the NK1R-positive profiles (Fig. 3F) in the outer lamina of the sham-operated animals. DRC injury reduced the pinch-evoked (Fig. 3E) and touch-evoked (Fig. 3F) internalization to 16 ± 3.0 % and 11 ± 2.5 % of the NK1R-expressing profiles, respectively. Neublazin treatment after DRC preserved the responses of post-synaptic
25 dorsal horn neurons; noxious mechanical stimulation resulted in internalization of the NK1 receptor in 85 ± 3.7 % (Fig. 3E) and light brush caused internalization in 57 ± 3.1 % (Fig. 3F) of the NK1-expressing dorsal horn neurons, thus indicating a significant restoration of SP-NK-1 receptor synaptic responses. Neublazin treatment did not alter the responses of sham-operated animals in these studies.

30 Stimulation of the median nerve ipsilateral to DRC or sham-operation resulted in spinal cord field potentials within 1 ms of stimulation (Fig. 4, top panel). These field

potentials are generated by volleys of action potentials in large myelinated cutaneous and proprioceptive axons in dorsal roots while those appearing 2 to 10 ms later represent monosynaptic excitatory post-synaptic potentials (EPSPs) evoked by the nerve stimulation (Fig. 4, bottom panel). The EPSPs were abolished following DRC and vehicle treatment. Five of 6 rats neublastin-treated rats showed clear EPSPs on the crush side, indicating that axons in the lesioned roots had regenerated and formed functioning synapses. In contrast, none of the 8 rats injected with vehicle showed appreciable recovery of synaptic potentials on the crush side. No significant differences were observed between maximal responses recorded on the intact side of neublastin-treated versus vehicle-treated animals.

Example 5: Systemic Neublastin Restores Sensorimotor Functions

Sensorimotor function was evaluated by the stabilization maneuver (Ramer et al. (2002) Mol. Cell. Neurosci. 19:239-49) in which the rat is nudged from behind and responds by placing the forelimbs in outstretched position, palms flat and toes outspread. Vehicle-treated rats with DRC consistently failed to respond with the stabilization maneuver (Fig. 5A). In contrast, the neublastin-treated rats showed a progressive recovery of the stabilization maneuver within 7 days, achieving nearly normal responses by day 14 and fully recovering, although more gradually, by 6 weeks (Fig. 5A) and remaining at normal levels at the 6 month observation point (Fig. 6D).

Impairment of sensory function, indicated by abnormal forelimb motion, impaired or inappropriate targeting, failure to bear weight or failure to use the forepaw entirely when walking on a 3-cm narrow beam (Ramer et al. (2002) Mol. Cell. Neurosci. 19:239-49) was graded from 0 (no limb use) to 5 (normal) by an observer blinded to the treatments. Animals with DRC injury showed complete disruption of limb use and scores were consistently less than 1 over the entire 42 day testing period (Fig. 5B). Neublastin produced a gradual, progressive improvement in beam-walking ability during the first 14 days, and continued improvement was noted beyond termination of neublastin injections (day 11), progressing at a slower rate over the remainder of the 42 day observation period (Fig. 5B) and normal 6 months later (Fig. 6E). Forelimb sensory deficit was further tested by allowing the rats to traverse a ladder oriented horizontally and counting the

incidence of slipping of a forepaw from the ladder (Ramer et al. (2002) Mol. Cell. Neurosci. 19:239-49). Sham-operated animals rarely registered "foot-slips" while traversing the ladder whereas rats with DRC injury demonstrated an average of 14 incidents per trial (Fig. 5C). Neublastin treatment resulted in a gradual, progressive improvement in the ability of the rats to walk across the ladder (Fig. 5C).

Improvement in sensorimotor function showed an apparent bi-phasic pattern, with rapid and very substantial improvement over the first 14 day period followed by a continued, but slower improvement of function over the remaining 42 days (Figs. 5A-5C), reaching normal levels at the 6 month observation point (Figs. 6D-6F). Neublastin treatment did not produce any changes in behavior of sham-operated rats (Figs. 5A-5C and Figs. 6D-6F).

Contact-evoked grasping was used as a measure of a highly complex sensorimotor response that is organized at supraspinal levels (Ramer et al. (2002) Mol. Cell. Neurosci. 19:239-49). Sham-operated rats lowered towards a cage consistently grasped the lid. This response was completely abolished by DRC injury (Fig. 5D), and these rats would make forward-directed, waving-like movements of the forelimb, but grasping was never accomplished (Ramer et al. (2002) Mol. Cell. Neurosci. 19:239-49). Treatment with systemic Neublastin produced a gradual, but consistently progressive, restoration of contact-evoked grasping (Fig. 5D) that was monophasic over the entire 42 day observation period. Contact-evoked grasping reached normal levels at the 6 month observation point (Fig. 6G).

Example 6: Systemic Neublastin Produces Long-Lasting Functional Recovery from Dorsal Root Injury

Responses to nociceptive stimuli described above were largely abolished by DRC and remained absent 6 months after the injury (Figs. 6A-6C) in vehicle treated animals. The essentially complete restoration of responses to noxious thermal, mechanical and chemical stimuli produced by Neublastin treatment was still present 6 months after DRC (Figs. 6A-6C) thus indicating the persistent restoration of normal nociceptive function by Neublastin treatment. As described above, the Neublastin-induced restoration of sensorimotor functions assessed by placement/stabilization, beam walking, horizontal

ladder, and grasping tests was maintained 6 months after DRC (Figs. 6D-6G). Neublastin did not change the behavioral responses of the sham-operated rats over the same time period. These data suggest that a limited schedule of neublastin treatment produces persistent restoration of sensorimotor function as well as responses to noxious stimuli.

5 Consistent with the persistent improvement in sensorimotor behavioral function, synaptic function was also maintained at these later times as shown by the recovery of formalin-evoked expression of FOS in the spinal dorsal horn (Fig. 6H). Additionally, three neublastin-treated rats were assessed electrophysiologically at 7 – 8 months post-lesion, and all 3 showed clear evidence of sensory-evoked EPSPs in the spinal cord. In
10 contrast, none of the 3 vehicle-treated rats tested at this time point had measurable synaptic inputs (Fig. 4).

The neurochemical indices of regeneration of axons through the DREZ were consistent with the behavior observed 6 months after the injury. The restoration of immunofluorescent labeling for CGRP, P2X₃ and CTB into the spinal dorsal horn was
15 still evident 6 months after DRC in the neublastin-treated animals, but was completely absent in spinal sections from vehicle-treated rats with DRC. Most striking was the appearance of labeling for CTB in the n. cuneatus 6 months after DRC in neublastin-treated, but not vehicle-treated, rats. This marker was not present in the n. cuneatus 14
20 days after the injury, suggesting that regeneration of myelinated afferent fibers to this supraspinal nucleus occurs over a prolonged time-course after injury and following neublastin treatment, consistent with the slow rate of restoration of complex sensorimotor behavior indicated by contact-evoked grasping.

25 Example 7: Differential Expression of GFR α 3 In Peripheral Nerves Correlates with Recovery of Sensory Modalities

Since neublastin acts through the GFR α 3 receptor coupled to the RET signaling protein, DRC-induced changes in expression of GFR α 3 or RET among the different types of peripheral nerves may influence their regeneration. Neublastin treatment did not alter GFR α 3 or RET expression in any fiber types of sham-operated animals. When
30 measured 14 days after sham surgery, the percentage of DRG profiles that expressed GFR α 3 were 34 ± 1.9 and 33 ± 3.1 for the vehicle-treated and neublastin-treated groups,

respectively and the percentage expressing RET were 59 ± 2.8 and 61 ± 1.5 (Fig. 7A). The percent of profiles from the DRG of rats with DRC and vehicle treatment that expressed GFR α 3 was significantly increased to 52 ± 1.8 whereas that expressing RET was decreased to 40 ± 1.23 (Fig. 7B). Treatment with neublastin largely normalized these changes, and the corresponding percentages of DRG profiles expressing GFR α 3 was 47 ± 6.14 and that expressing or RET was 49 ± 2.72 . Co-labeling for GFR α 3 or for RET and for either N52, CGRP or P2X₃ was examined in order to identify changes in myelinated peripheral nerves (N52) and unmyelinated peptidergic (CGRP) and non-peptidergic (P2X₃) nociceptors. 14 ± 0.5 % of the DRG profiles of sham-operated, vehicle-treated rats co-labeled GFR α 3 and N52 and 22 ± 0.85 % of the DRG profiles co-expressed RET and N52, indicating that a significant proportion of myelinated peripheral nerves are subject to modulation by neublastin. Neublastin treatment did not change these proportions in sham-operated rats (Figs. 7A and 7B). The proportion of DRG profiles that labeled both GFR α 3 and N52 was reduced to 5 ± 1.2 % and that expressing N52 and RET was reduced to 5 ± 0.9 % (Figs. 7A and 7B). In contrast, there was a near doubling of DRG profiles immunoreactive for either CGRP or P2X₃ and for GFR α 3 while those also labeling RET remained unchanged (Figs. 7A and 7B). Neublastin treatment resulted in a normalization of the proportions of DRG neuronal populations expressing these markers (Figs. 7A and 7B), and largely prevented the loss of co-labeling for N52 and either GFR α 3 or RET caused by DRC.

Example 8: Neublastin does not Alter the Characteristics of the DREZ

Immunoreactivity to glial fibrillary acidic protein (GFAP), which identifies astrocytes, and to ED1, which labels activated microglia, were markedly increased by DRC. Treatment with neublastin did not produce any changes in labeling for either GFAP or ED1 after DRC injury. Therefore, it is likely that the regeneration of axons and functional recovery of sensory modalities induced by neublastin was due to enhanced survival of the axon growth cones and stimulation of regeneration rather than to a breakdown of the inhibitory barriers in the DREZ.

Example 9: Timing-Based Neublastin Administration Post Dorsal Root Injury Facilitates Functional Recovery

Clinically, immediate treatment to a dorsal root injury is not always available. To mimic clinical conditions and to examine the window of opportunity for Neublastin treating dorsal root injury efficiently, Neublastin was administered in a delayed time courses.

When given subcutaneously starting at day 2 post dorsal root injury, Neublastin restored the thermal and mechanical function almost completely, reached the maximum recovery at day 10 post injury, and then remained at a similar level until the end of experiment at day 28 post root injury. When injected subcutaneously starting at day 4 post dorsal rhizotomy, Neublastin recovered thermal function fully and recovered mechanical function partially. Neublastin treatment still significantly restored the mechanical response at day 9 post surgery after 3 injections, compared to the vehicle treatment. When given at day 7 post root injury, Neublastin exerted the ability of restoring the function to the thermal stimuli significantly, but lost the ability of responding to mechanical stimuli.

In line with the shifts of functional recovery in delayed Neublastin treatment, the labeling of three types of afferents in spinal dorsal horn also changed with the time of delayed Neublastin treatment. The dramatic changes were seen in CTB labeling, though CGRP and P2X3 labeling also exhibited some changes. When Neublastin was given starting at day 2 post root injury, the spinal density of CTB labeling was around 50% of normal level at day 28 post dorsal root injury. When Neublastin was given at day 4 post root injury, the number was about 25%, when Neublastin was injected starting at day 7 post dorsal root crush, the number was about 5 percent. However, the CGRP and P2X3 labeling was maintained 35% or above of the normal level at day 28 post root injury for delayed Neublastin treatments. Delayed vehicle treatment did not change the labeling density of the three types of sensory axons in the spinal dorsal horn.

Example 10: Systemic Neublastin Promotes Peripheral Nerve Regeneration and Recovery of Mechanical and Thermal Hypersensitivity in Animals that have Undergone Nerve Crush Distal to the Dorsal Root Ganglia

5 The L5 spinal nerve of anesthetized rats was exposed and (i) tightly ligated with sutures according to the procedure of Kim and Chung (Kim et al. (1992) *Pain* 50:355-63) ("nerve ligation"), (ii) crushed as described in Example 1 ("nerve crush"), or (iii) cut ("nerve section"). Sham surgery was processed under the same procedures without nerve injury. Rat neublastin or saline vehicle was given subcutaneously on a Monday, Wednesday, and Friday schedule immediately after surgery for a total of 6 injections over
10 2 weeks.

 The Von Frey (Chaplan et al. (1994) *J. Neurosci. Meth.* 53:55-63) and Hargreaves (Hargreaves et al. (1988) *Pain* 32:77-88) behavioral tests were used to monitor tactile and thermal pain responses, respectively. Five weeks post-surgery, the neuronal tracers CTB and Dextran were injected into the sciatic nerve at the mid-thigh (distal to the nerve
15 injury). Six weeks post-surgery, rats were perfused for histological study.

 Tactile allodynia and thermal hyperalgesia measurements were recorded on injured and sham injured animals treated with neublastin or vehicle. Animals with nerve injury and treated with vehicle showed no improvement in pain responses, with little change in responses throughout the six week evaluation (Figs. 8A-8D and 9A-9D).
20 Acute systemic neublastin administration caused an improvement of both tactile allodynia (Figs. 8A-8D) and thermal hyperalgesia (Figs. 9A-9D) thresholds following nerve section, nerve ligation, and nerve crush. In the nerve crush rats, the recovery of tactile allodynia persisted after the neublastin administration was terminated and was observed throughout the entire six week evaluation period (Fig. 8D).

25 Dextran, a neuronal tracer for labeling small diameter sensory fibers in the normal peripheral nervous system, was injected into the sciatic nerve (mid-thigh, distal to the nerve injury) and labeled neurons in the L5 DRG were subsequently examined. Systemic neublastin administration was found to promote regeneration of Dextran-labeled sensory fibers in the L5 nerve crush rats.

30 CTB, a neuronal tracer for labeling myelinated sensory fibers in the normal peripheral nervous system, was injected into the sciatic nerve (mid-thigh, distal to the

nerve injury) and labeled neurons in the L5 DRG were subsequently examined. Systemic neublastin administration was found to promote regeneration of CTB-labeled sensory fibers in the L5 nerve crush rats.

5 IB4, CGRP, and N52 immunolabelling was employed to visualize, respectively, non- peptidergic sensory fibers, peptidergic sensory fibers, and myelinated sensory fibers (these three biomarkers collectively label all populations of sensory biomarkers). Systemic neublastin administration was found to promote regeneration of all three types of sensory fibers in the L5 spinal nerve (distal to the crush site).

10

Other Embodiments

While the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

1. A method of improving impaired proprioception in a subject, the method comprising administering to a subject that exhibits impaired proprioception an amount of
5 a polypeptide effective to improve proprioception in the subject, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.
- 10 2. A method of regenerating nerve fibers in a subject, the method comprising administering to a subject that has suffered damage to or loss of nerve fibers an amount of a polypeptide effective to regenerate nerve fibers, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID
15 NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.
3. The method of claim 2, wherein the nerve fibers are large nerve fibers.
4. The method of claim 2, wherein the nerve fibers are small nerve fibers.
- 20 5. The method of any of claims 2-4, wherein the subject has suffered damage to or loss of dorsal root nerve fibers.
6. The method of any of claims 2-4, wherein the subject has suffered damage to
25 or loss of nerve fibers distal to the dorsal root ganglia.
7. The method of any of claims 2-4, wherein the nerve fibers are nerve fibers of the skin and the administration of the polypeptide results in skin reinnervation.
- 30 8. The method of any of claims 2-7, wherein the polypeptide is administered to the subject within 48 hours following the damage to or loss of nerve fibers.

9. The method of any of claims 2-7, wherein the polypeptide is administered to the subject within seven days following the damage to or loss of nerve fibers.

5 10. The method of any of claims 2-7, wherein the polypeptide is administered to the subject within one month following the damage to or loss of nerve fibers.

11. The method of any of claims 2-10, wherein the polypeptide is administered to the subject in two or more doses following the damage to or loss of nerve fibers.

10

12. The method of any of claims 2-11, wherein administration of the polypeptide to the subject is terminated within six months following the damage to or loss of nerve fibers.

13. The method of any of claims 2-11, wherein administration of the polypeptide to
15 the subject is terminated within one month following the damage to or loss of nerve fibers.

14. The method of any of claims 2-11, wherein administration of the polypeptide to the subject is terminated within two weeks following the damage to or loss of nerve fibers.

20 15. The method of any of claims 2-14, wherein the damage to or loss of nerve fibers is a result of a nerve crush injury.

16. The method of any of claims 2-14, wherein the damage to or loss of nerve fibers is a result of a nerve cut injury.

25

17. A method of improving an impaired sensory neural response in a subject, the method comprising administering to a subject that exhibits an impaired sensory neural response an amount of a polypeptide effective to improve the impaired response, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino
30 acids 15-113 of SEQ ID NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.

18. The method of claim 17, wherein the impaired sensory neural response is a result of damage to or loss of dorsal root nerve fibers.

5 19. The method of claim 17, wherein the impaired sensory neural response is a result of damage to or loss of nerve fibers distal to the dorsal root ganglia.

20. The method any of claims 17-19, wherein the impaired sensory neural response is characterized by a loss of sensitivity to noxious mechanical or thermal
10 stimuli.

21. A method of treating a brachial plexus injury in a subject, the method comprising administering to a subject that has suffered a brachial plexus injury an effective amount of a polypeptide that comprises an amino acid sequence that is at least
15 80% identical to amino acids 15-113 of SEQ ID NO:1, wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.

22. The method of claim 21, wherein the polypeptide is administered to the subject within 48 hours following the brachial plexus injury.
20

23. The method of claim 21, wherein the polypeptide is administered to the subject within seven days following the brachial plexus injury.

24. The method of claim 21, wherein the polypeptide is administered to the subject
25 within one month following the brachial plexus injury.

25. The method of any of claims 21-24, wherein the polypeptide is administered to the subject in two or more doses following the brachial plexus injury.

30 26. The method of any of claims 21-25, wherein administration of the polypeptide to the subject is terminated within six months following the brachial plexus injury.

27. The method of any of claims 21-25, wherein administration of the polypeptide to the subject is terminated within one month following the brachial plexus injury.

5 28. The method of any of claims 21-25, wherein administration of the polypeptide to the subject is terminated within two weeks following the brachial plexus injury.

10 29. A method of treating a dorsal root nerve injury in a subject, the method comprising administering to a subject that has suffered loss of synaptic function as a result of a dorsal root nerve injury an amount of a polypeptide effective to promote reentry of nerve fibers through the dorsal root entry zone into the spinal cord, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.

15 30. The method of claim 29, wherein the polypeptide is administered to the subject within 48 hours following the dorsal root nerve injury.

20 31. The method of claim 29, wherein the polypeptide is administered to the subject within seven days following the dorsal root nerve injury.

32. The method of claim 29, wherein the polypeptide is administered to the subject within one month following the dorsal root nerve injury.

25 33. The method of any of claims 29-32, wherein the polypeptide is administered to the subject in two or more doses following the dorsal root nerve injury.

30 34. The method of any of claims 29-33, wherein administration of the polypeptide to the subject is terminated within six months following the dorsal root nerve injury.

35. The method of any of claims 29-33, wherein administration of the polypeptide to the subject is terminated within one month following the dorsal root nerve injury.

5 36. The method of any of claims 29-33, wherein administration of the polypeptide to the subject is terminated within two weeks following the dorsal root nerve injury.

37. The method of any of claims 1-36, wherein the polypeptide is administered to the subject via systemic administration.

10 38. The method of any of claims 1-36, wherein the polypeptide is administered to the subject via subcutaneous administration.

39. The method of any of claims 1-36, wherein the polypeptide is administered to the subject via intravenous administration.

15 40. The method of any of claims 1-36, wherein the polypeptide is administered locally to damaged neural tissue.

20 41. The method of any of claims 1-40, wherein the subject is a human.

42. A method of regenerating nerve fibers, the method comprising contacting neural tissue that has suffered damage to or loss of nerve fibers with an amount of a polypeptide effective to regenerate nerve fibers, wherein the polypeptide comprises an amino acid sequence that is at least 80% identical to amino acids 15-113 of SEQ ID
25 NO:1, and wherein the polypeptide, when dimerized, binds to a complex containing GFR α 3 and RET.

43. The method of claim 42, wherein the nerve fibers are large nerve fibers.

30 44. The method of claim 42, wherein the nerve fibers are small nerve fibers.

45. The method of any of claims 42-44, wherein the neural tissue comprises dorsal root ganglia.

46. The method of any of claims 42-44, wherein the neural tissue comprises nerve fibers distal to the dorsal root ganglia.

47. The method of claim 42, wherein the nerve fibers are nerve fibers of the skin.

48. The method of any of claims 42-47, wherein the neural tissue is contacted with the polypeptide within 48 hours following the damage to or loss of nerve fibers.

49. The method of any of claims 42-47, wherein the neural tissue is contacted with the polypeptide within seven days following the damage to or loss of nerve fibers.

50. The method of any of claims 42-47, wherein the neural tissue is contacted with the polypeptide within one month following the damage to or loss of nerve fibers.

51. The method of any of claims 42-50, wherein the neural tissue is contacted with the polypeptide in two or more doses following the damage to or loss of nerve fibers.

52. The method of any of claims 42-51, wherein the damage to or loss of nerve fibers is the result of a nerve crush injury.

53. The method of any of claims 42-51, wherein the damage to or loss of nerve fibers is the result of a nerve cut injury.

54. The method of any of claims 1-53, wherein the amino acid sequence is at least 90% identical to amino acids 15-113 of SEQ ID NO:1.

55. The method of any of claims 1-53, wherein the amino acid sequence is at least 95% identical to amino acids 15-113 of SEQ ID NO:1.

56. The method of any of claims 1-53, wherein the amino acid sequence is at least 98% identical to amino acids 15-113 of SEQ ID NO:1.

5 57. The method of any of claims 1-53, wherein the polypeptide comprises amino acids 15-113 of SEQ ID NO:1, amino acids 15-113 of SEQ ID NO:2, amino acids 15-113 of SEQ ID NO:3, amino acids 15-113 of SEQ ID NO:4, amino acids 15-113 of SEQ ID NO:5, amino acids 15-113 of SEQ ID NO:8, or amino acids 15-113 of SEQ ID NO:9.

10 58. The method of any of claims 1-53, wherein the polypeptide comprises the amino acid sequence of SEQ ID NO:1, the amino acid sequence of SEQ ID NO:2, the amino acid sequence of SEQ ID NO:3, the amino acid sequence of SEQ ID NO:4, the amino acid sequence of SEQ ID NO:5, the amino acid sequence of SEQ ID NO:8, or the amino acid sequence of SEQ ID NO:9.

15 59. The method of any of claims 1-53, wherein the polypeptide comprises amino acids 10-113 of SEQ ID NO:1.

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		10	20	30	40	50
Human Neubla...	1	MELGLGGLST	LSHCWPWRQ	PALWPTLAAL	ALLSSVAEAS	LGSAPRSPAP
Mouse Neubla...	1	MELGLAEPTA	LSHCLRPRWQ	SAWWPTLAVL	ALLSCVTEAS	LDPMSPSPAA
Rat Neublastin	1	MELGLGEPTA	LSHCLRPRWQ	PALWPTLAAL	ALLSSVTEAS	LDPMSPSPAS
Human Neubla...	51	REGPPVPLAS	PAGHLPGGRT	ARWCSGRARR	PPPQPSRPAP	PPPAP---P
Mouse Neubla...	51	RDGPSPVLAP	PTDHLPGGHT	AHLCSERTLR	PPPQSPQAP	PPPGPALQSP
Rat Neublastin	51	RDVPSPVLAP	PTDYLPGGHT	AHLCSERALR	PPPQSPQAP	PPPGPALQSP
Human Neubla...	97	SALPRGCRRA	RAGGPCSRAR	AAGARGCRLR	SQLVPVRALG	LGHRSDDELVR
Mouse Neubla...	101	PAALRGARAA	RAGTRSSRAR	TTDARGCRLR	SQLVPVSALG	LGHSSDELIR
Rat Neublastin	101	PAALRGARAA	RAGTRSSRAR	ATDARGCRLR	SQLVPVSALG	LGHSSDELIR
Human Neubla...	147	FRFCSGSQR	ARSPHDLSLA	SLLGAGALRP	PPGSRPVSQP	CCRPTRYEAV
Mouse Neubla...	151	FRFCSGSQR	ARSDHLSLA	SLLGAGALRS	PPGSRPI SQP	CCRPTRYEAV
Rat Neublastin	151	FRFCSGSQR	ARSPHDLSLA	SLLGAGALRS	PPGSRPI SQP	CCRPTRYEAV
Human Neubla...	197	SFMDVNSTWR	TVDRLSATA	GCLG		
Mouse Neubla...	201	SFMDVNSTWR	TVDHLSATA	GCLG		
Rat Neublastin	201	SFMDVNSTWR	TVDHLSATA	GCLG		

FIG. 1

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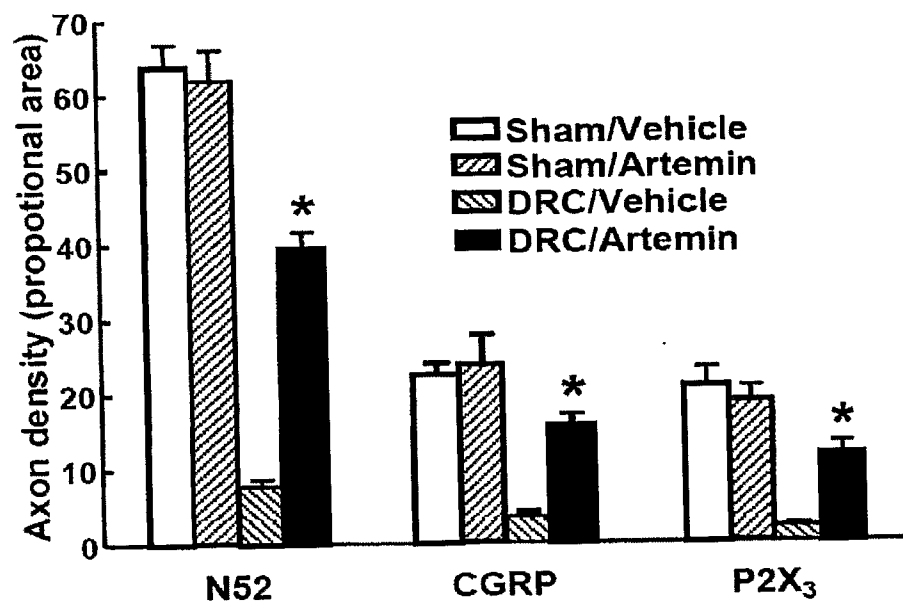


FIG. 2

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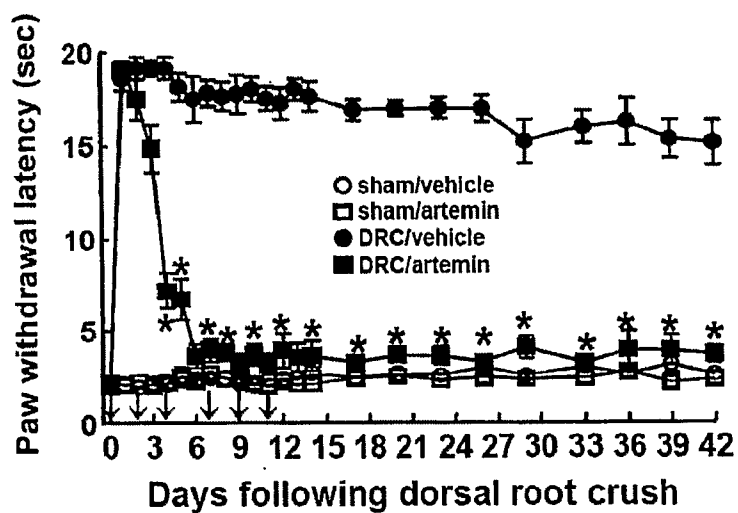


FIG. 3A

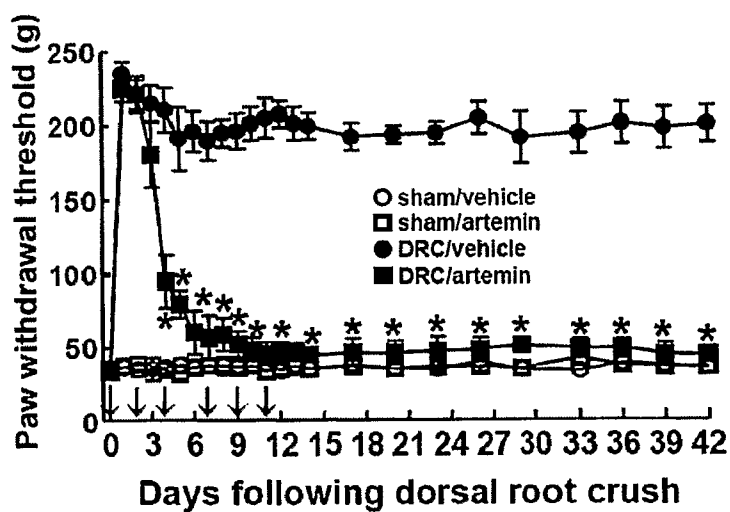


FIG. 3B

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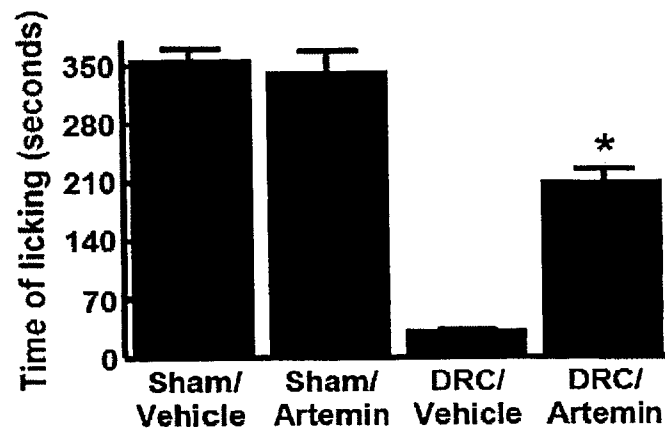


FIG. 3C

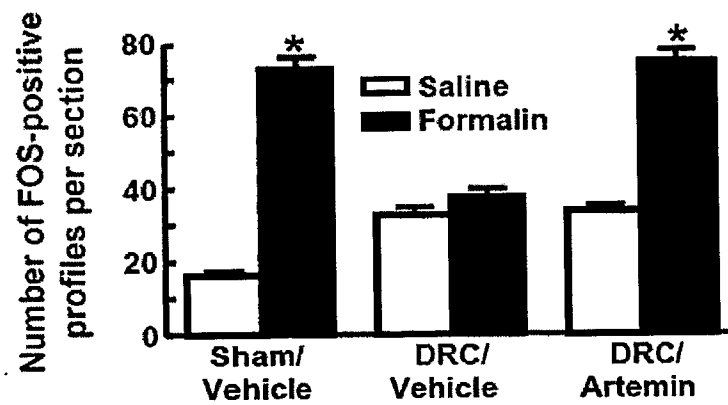


FIG. 3D

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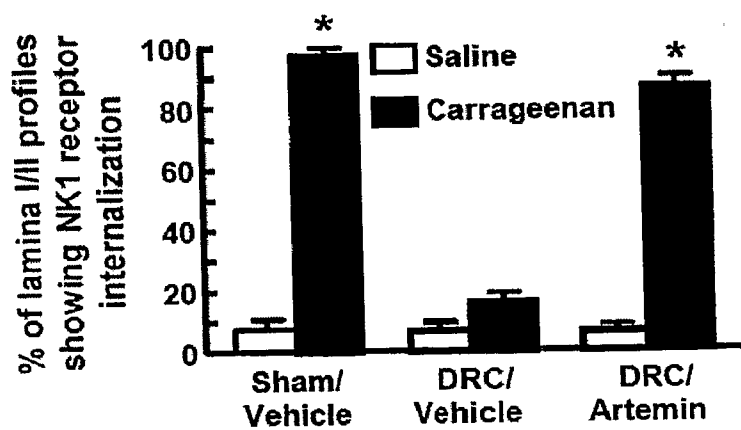


FIG. 3E

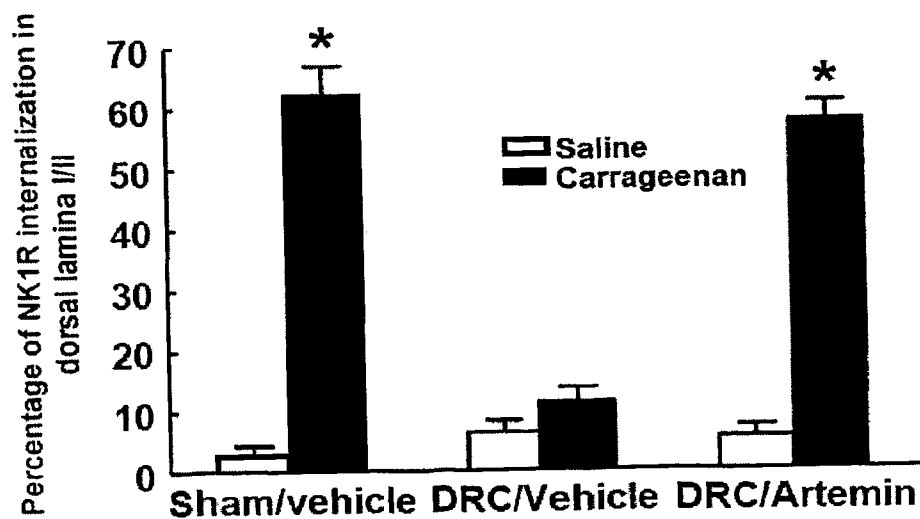


FIG. 3F

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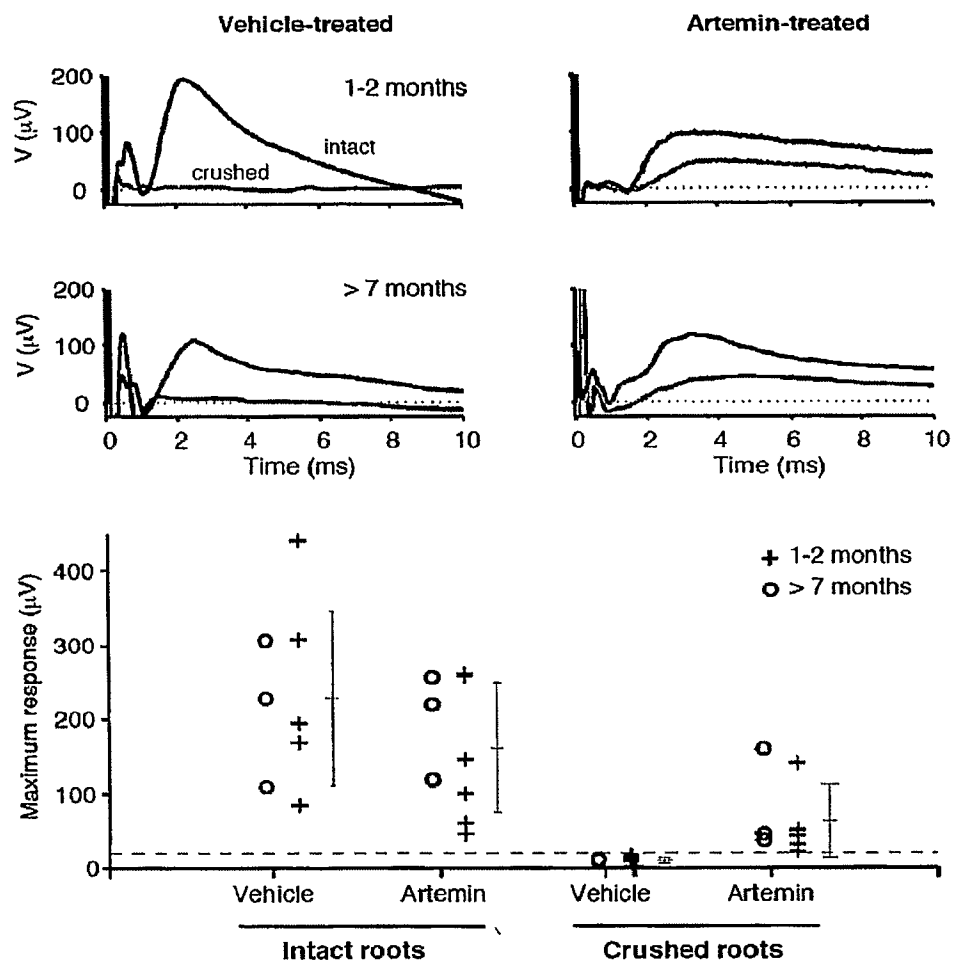


FIG. 4

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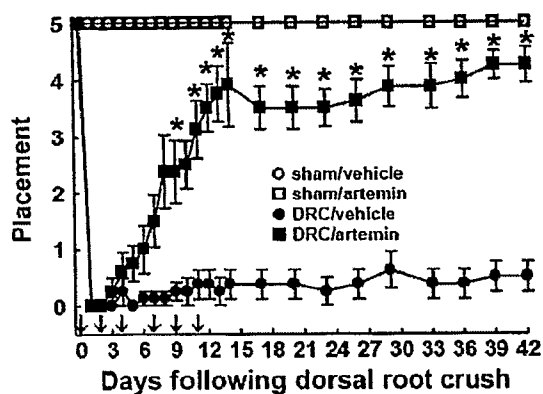


FIG. 5A

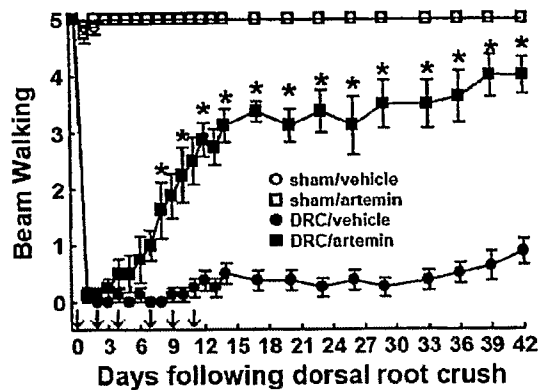


FIG. 5B

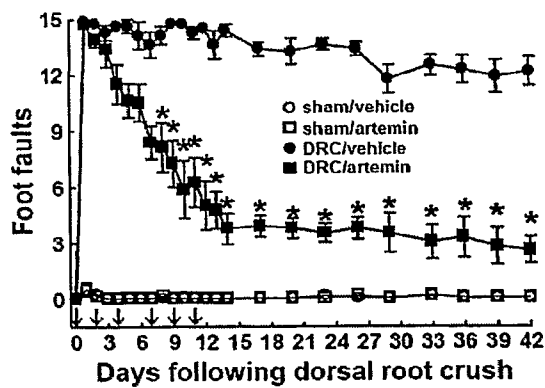


FIG. 5C

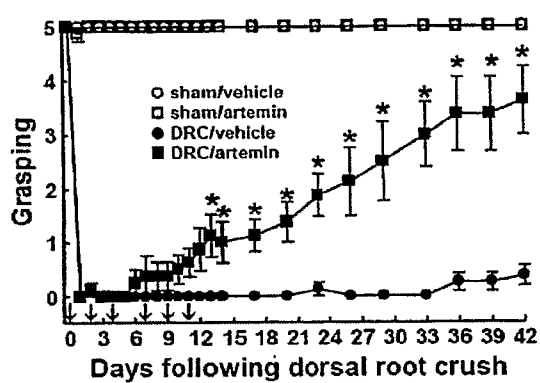


FIG. 5D

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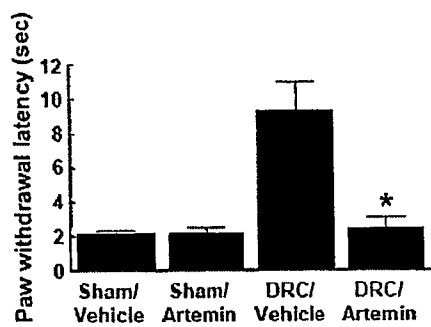


FIG. 6A

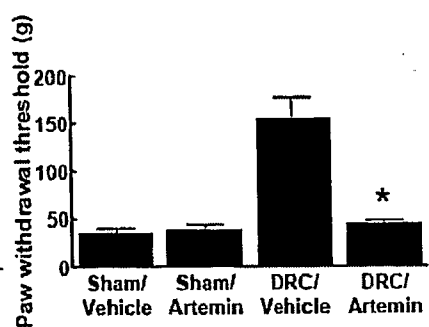


FIG. 6B

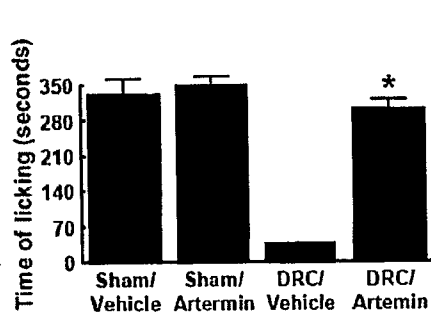


FIG. 6C

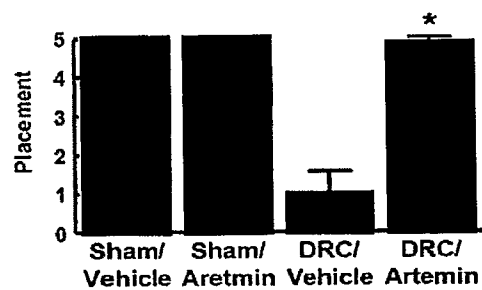


FIG. 6D

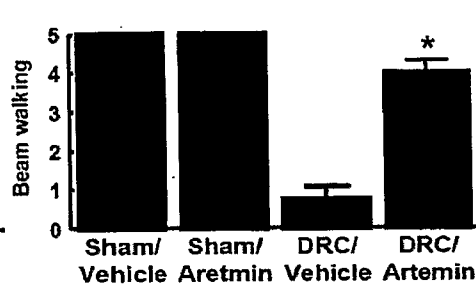


FIG. 6E

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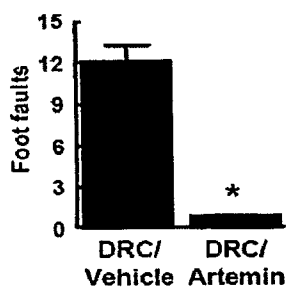


FIG. 6F

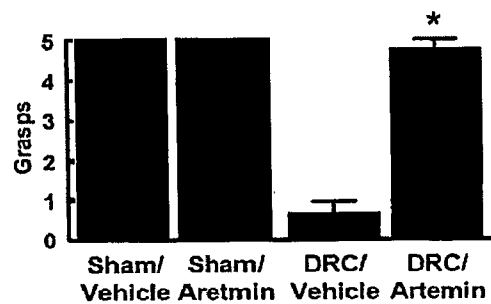


FIG. 6G

6 Months after DRC

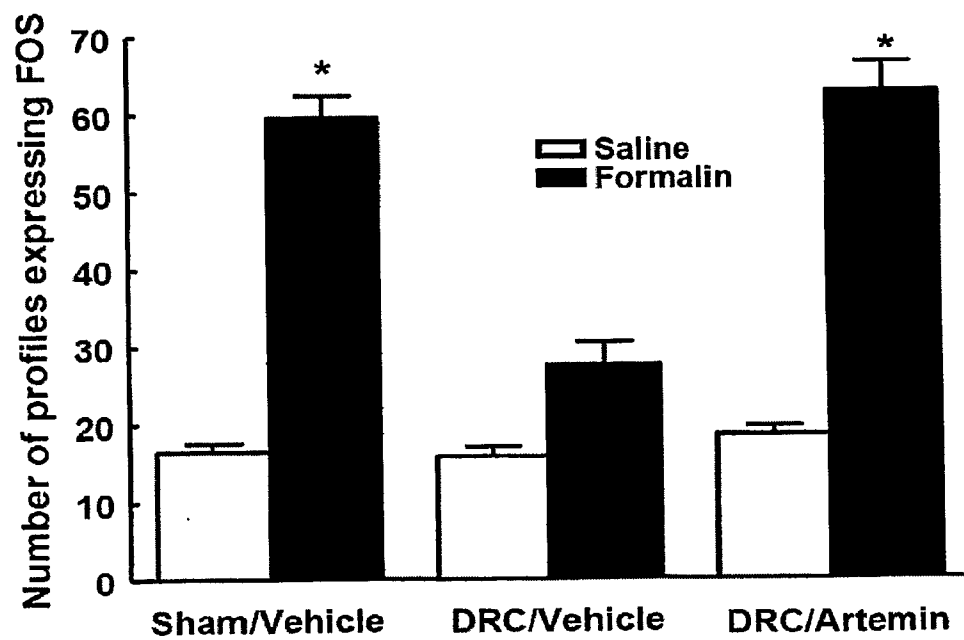


FIG. 6H

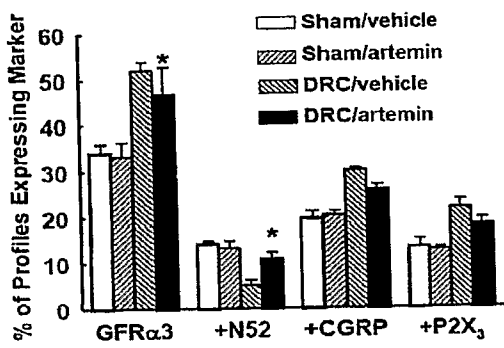


FIG. 7A

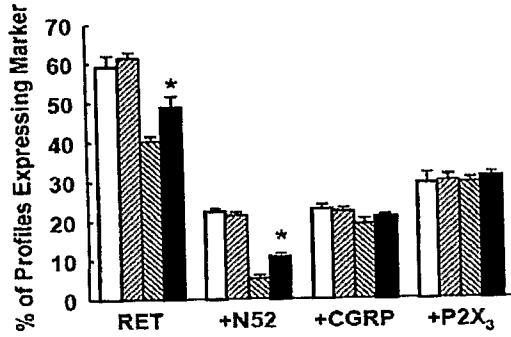


FIG. 7B

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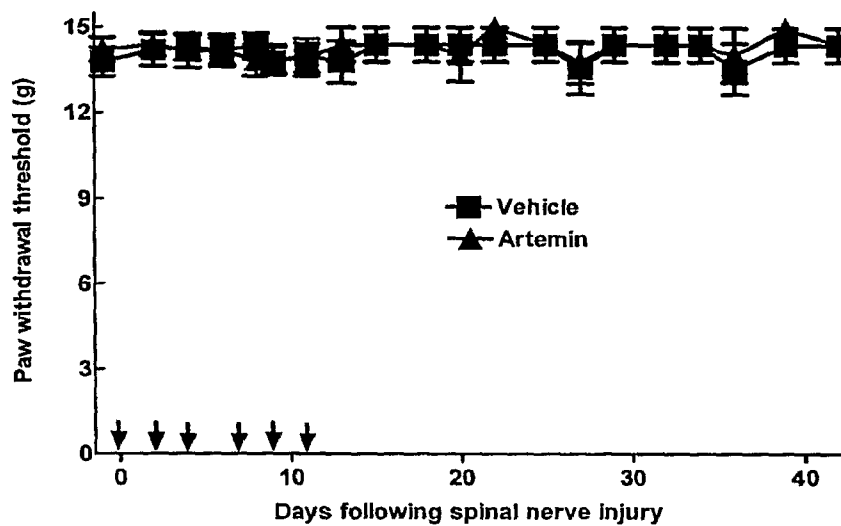


FIG. 8A

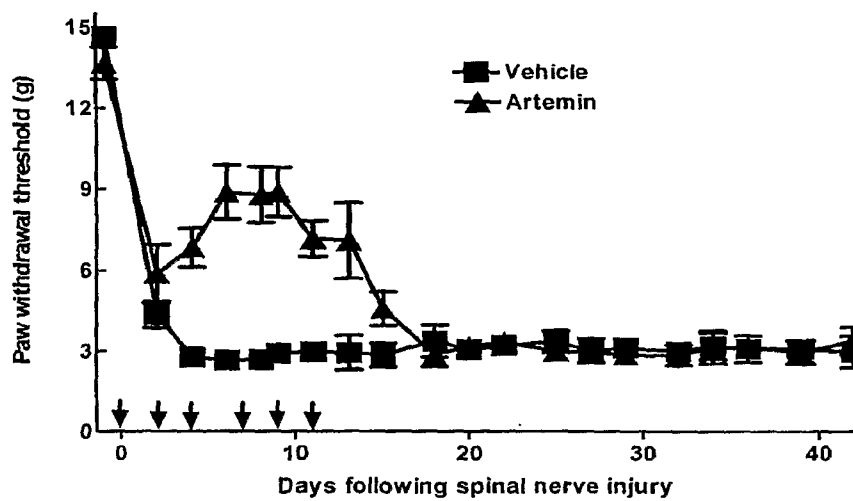


FIG. 8B

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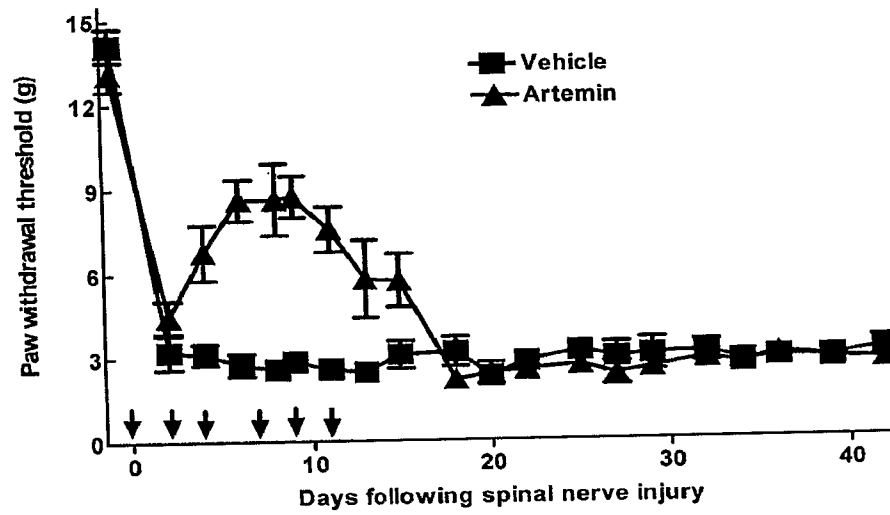


FIG. 8C

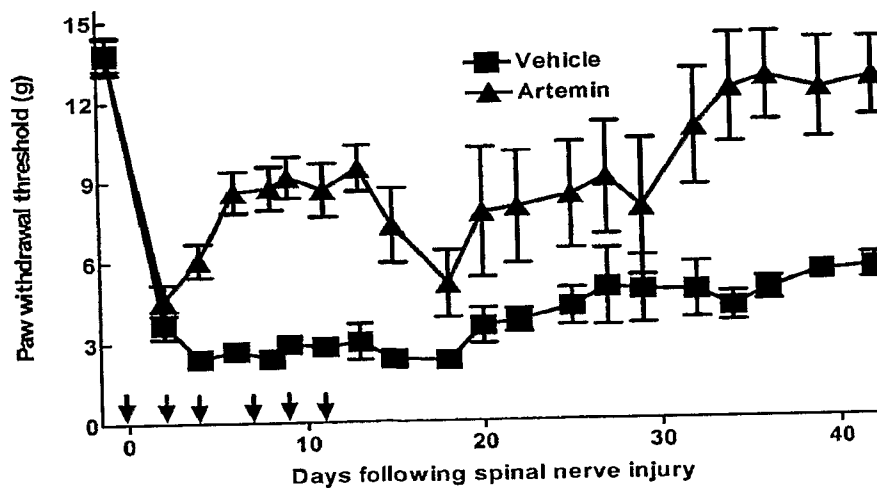


FIG. 8D

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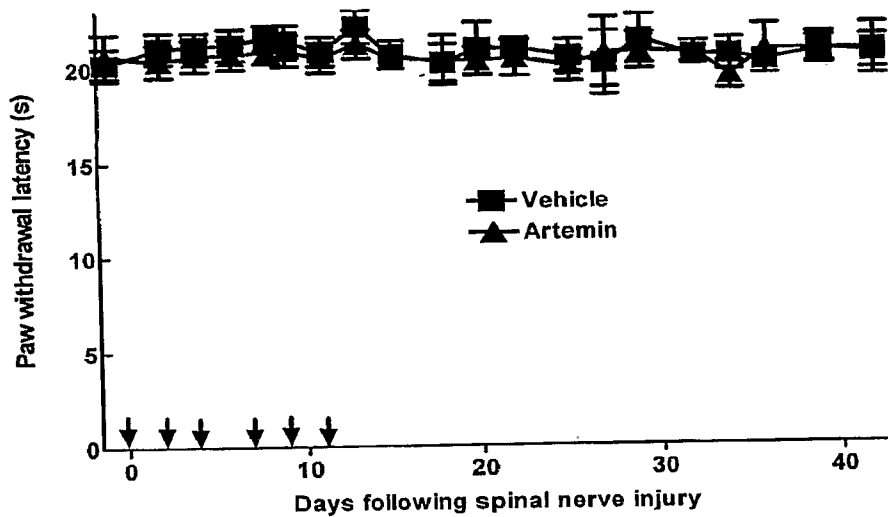


FIG. 9A

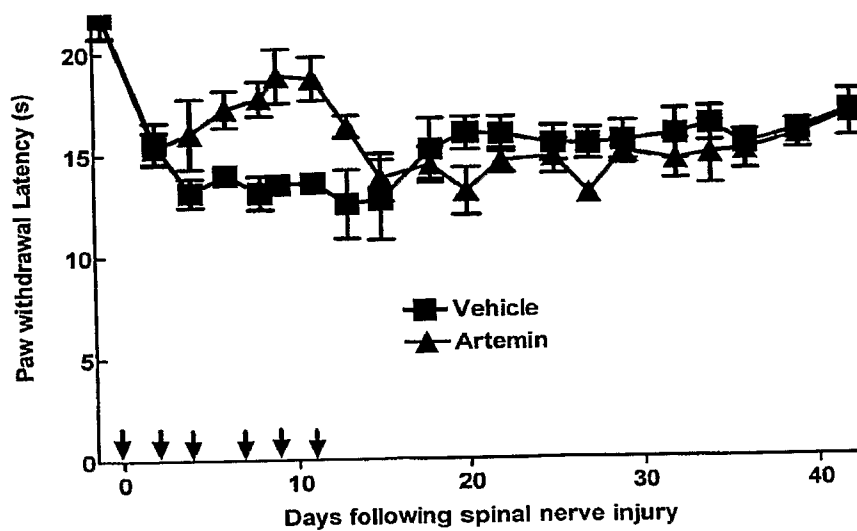


FIG. 9B

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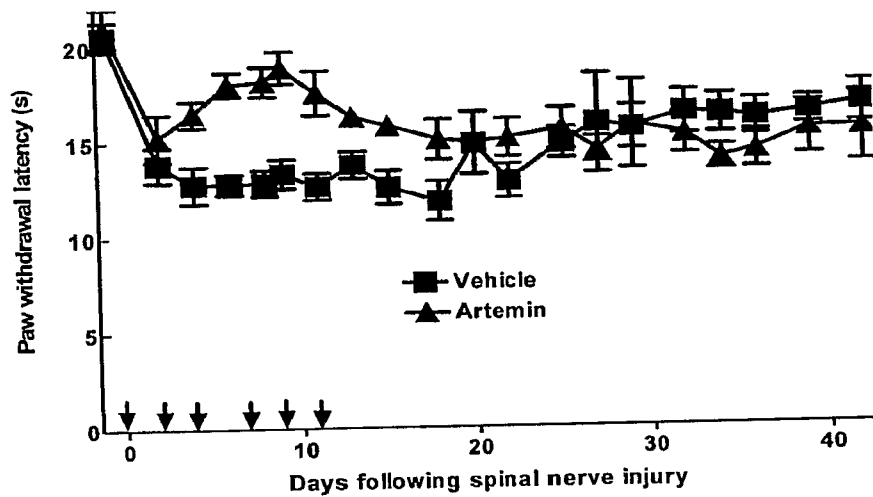


FIG. 9C

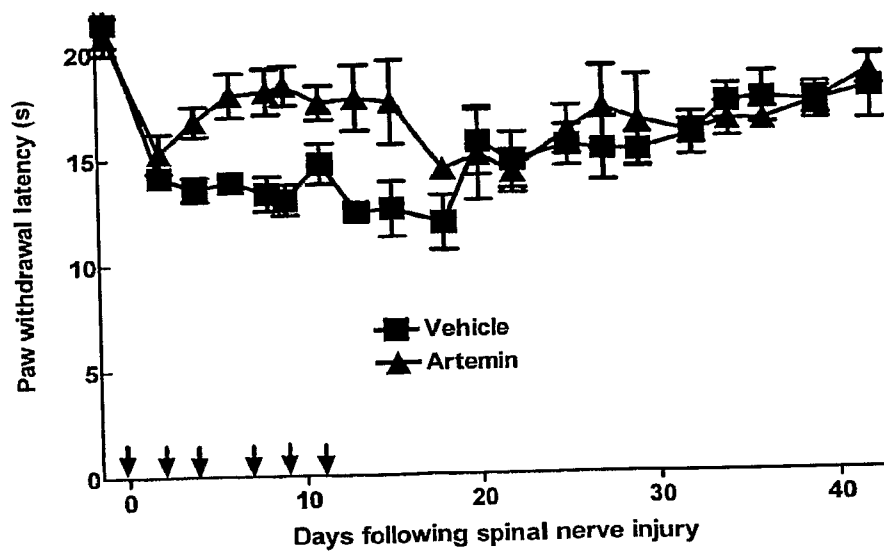


FIG. 9D