

WO 2013/059791 A2

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property  
Organization  
International Bureau



(10) International Publication Number

WO 2013/059791 A2

(43) International Publication Date  
25 April 2013 (25.04.2013)

(51) International Patent Classification:

*A61K 31/27* (2006.01)    *A61K 45/06* (2006.01)  
*A61K 31/4178* (2006.01)    *A61P 25/28* (2006.01)

(21) International Application Number:

PCT/US2012/061324

(22) International Filing Date:

22 October 2012 (22.10.2012)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/550,191    21 October 2011 (21.10.2011)    US

(71) Applicant: MASSACHUSETTS EYE AND EAR IN-  
FIRMARY [US/US]; 243 Charles Street, Boston, MA  
02114 (US).

(72) Inventor: VAVVAS, Demetrios; 19 Hemman Street, Bo-  
ston, MA 02131 (US).

(74) Agents: GUSTAFSON, Megan, A. et al.; Goodwin  
Procter LLP, Exchange Place, Boston, MA 02109 (US).

(81) Designated States (unless otherwise indicated, for every  
kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,  
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,  
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,  
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP,  
KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD,  
ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,  
NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU,  
RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ,  
TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA,  
ZM, ZW.

(84) Designated States (unless otherwise indicated, for every  
kind of regional protection available): ARIPO (BW, GH,  
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,  
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,  
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,  
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,  
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,  
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,  
ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished  
upon receipt of that report (Rule 48.2(g))

(54) Title: METHODS AND COMPOSITIONS FOR PROMOTING AXON REGENERATION AND NERVE FUNCTION

(57) Abstract: Provided are methods for promoting axon regeneration of Central Nervous System (CNS) neuron and promoting nerve function following injury to a CNS neuron, for example, brain and/or spinal cord injury. Axon regeneration in a CNS neuron or nerve function following injury to a CNS neuron can be promoted by administering a necrosis inhibitor either alone or in combination with an apoptosis inhibitor to a subject suffering from a CNS disorder, wherein a symptom of the CNS disorder is axon degeneration.

## METHODS AND COMPOSITIONS FOR PROMOTING AXON REGENERATION AND NERVE FUNCTION

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to United States Provisional Patent Application No. 61/550,191, filed October 21, 2011, the contents of which are hereby incorporated by reference in their entirety.

### GOVERNMENT FUNDING

[0002] The work described in this application was sponsored, in part, by the National Eye Institute under Grant No. EY14104. The United States Government has certain rights in the invention.

### FIELD OF THE INVENTION

[0003] The field of the invention relates generally to methods for promoting axon regeneration. More particularly, the invention relates to the use of a necrosis inhibitor, *e.g.*, a RIP kinase inhibitor, *e.g.*, a necrostatin, either alone or in combination with an apoptosis inhibitor, *e.g.*, a pan-caspase inhibitor, for preserving neuron viability, promoting nerve function, and enhancing axon outgrowth.

### BACKGROUND OF THE INVENTION

[0004] The nervous system is divided into two parts: the central nervous system (CNS), which includes the brain and the spinal cord, and the peripheral nervous system, which includes nerves and ganglia outside of the brain and the spinal cord. While the peripheral nervous system is capable of repair and regeneration, the central nervous system is unable to self-repair and regenerate.

[0005] In the United States, traumatic injuries to the CNS such as traumatic brain injury and spinal cord injury affect over 90,000 people each year. Furthermore, neurodegenerative diseases such as dementia, stroke, Alzheimer's disease, Parkinson's disease, and Huntington's

- 2 -

disease affect millions of people worldwide. These traumatic and age-related insults to the CNS cause axonal loss, disrupt neuronal connections, and ultimately result in permanent blindness, paralysis, and other losses in cognitive, motor, and sensory functions. There is currently no effective treatment for recovering human nerve functions after CNS injury.

5 [0006] Apoptosis and necrosis represent two different mechanisms of cell death. Apoptosis is a highly regulated process involving the caspase family of cysteine proteases, and characterized by cellular shrinkage, chromatin condensation, and DNA degradation. In contrast, necrosis is associated with cellular and organelle swelling and plasma membrane rupture with ensuing release of intracellular contents and secondary inflammation (Kroemer *et al.*, (2009) CELL DEATH DIFFER 16:3-11). Necrosis has been considered a passive, unregulated form of cell death; however, recent evidence indicates that some necrosis can be induced by regulated signal transduction pathways such as those mediated by receptor interacting protein (RIP) kinases, especially in conditions where caspases are inhibited or cannot be activated efficiently (Golstein P & Kroemer G (2007) TRENDS BIOCHEM. SCI. 32:37-43; Festjens *et al.* 10 (2006) BIOCHIM. BIOPHYS. ACTA 1757:1371-1387). Stimulation of the Fas and TNFR family of death domain receptors (DRs) is known to mediate apoptosis in most cell types through the activation of the extrinsic caspase pathway. In addition, in certain cells deficient for caspase-8 or treated with pan-caspase inhibitor ZVAD, stimulation of death domain receptors (DR) causes a RIP-1 kinase dependent programmed necrotic cell death instead of apoptosis (Holler *et 15 al.* (2000) NAT. IMMUNOL. 1:489-495; Degterev *et al.* (2008) NAT. CHEM. BIOL. 4:313-321). This novel mechanism of cell death is termed “programmed necrosis” or “necroptosis” (Degterev *et al.*, (2005) NAT CHEM BIOL 1:112-119).

20 [0007] Receptor Interacting Protein kinase 1 (RIP-1) is a serine/threonine kinase that contains a death domain and forms a death signaling complex with the Fas-associated death domain and caspase-8 in response to death receptor (DR) stimulation (Festjens *et al.* (2007) CELL DEATH DIFFER. 14:400-410). During death domain receptor-induced apoptosis, RIP-1 is cleaved and inactivated by caspase-8, the process of which is prevented by caspase inhibition (Lin *et al.* (1999) GENES. DEV. 13:2514-2526). It has been unclear how RIP-1 kinase mediates programmed necrosis, but recent studies revealed that the expression of RIP-3 and the RIP-1- 25 RIP-3 binding through the RIP homotypic interaction motif is a prerequisite for RIP-1 kinase activation, leading to reactive oxygen species (ROS) production and necrotic cell death (He *et 30 al.*

*al.*, (2009) CELL 137:1100-1111; Cho *et.al.*, (2009) CELL 137:1112-1123; Zhang *et al.*, (2009) SCIENCE 325:332-336).

[0008] There is still an ongoing need to minimize or eliminate neuronal cell death and promote neuronal regeneration and axonal growth in patients affected with a CNS disorder 5 such as, for example, traumatic CNS injuries and neurodegenerative diseases.

#### SUMMARY OF THE INVENTION

[0009] The invention is based, in part, on the discovery that a necrosis inhibitor, *e.g.*, RIP kinase inhibitor, *e.g.*, a necrostatin, *e.g.*, necrostatin-1, can be used to preserve neuron viability and promote axon growth and nerve functions. The studies described herein indicate that programmed necrosis may be a critical mechanism for CNS disorders wherein symptoms of the 10 disorder include neuronal cell death, axon degeneration, and/or impaired axon growth. As a result, it may be possible to reduce or even reverse the loss of cognitive, motor, and sensory functions associated with a CNS disorder, by preserving neuron viability and/or promoting axon regeneration and/or nerve functions.

[0010] In one aspect, the invention provides a method for promoting axon regeneration in a 15 CNS neuron by exposing the CNS neuron to an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote the regeneration of the axon. The CNS neuron may be *ex vivo* or *in vivo*. The CNS neuron may include, but is not limited to, a CNS sensory neuron, a motor neuron, a cortical neuron, a cerebellar neuron, a hippocampal neuron, and a midbrain neuron.

[0011] In another aspect, the invention provides a method for promoting nerve function 20 following injury to a CNS neuron. The method comprises administering to a subject an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote CNS neuron function. In a further aspect, the invention provides a method for preserving the viability of a CNS neuron, wherein the method comprises administering to a 25 subject an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to preserve the viability of the CNS neuron. After administration of the necrosis inhibitor and the apoptosis inhibitor, the CNS neuron may be capable of supporting axonal regeneration.

- 4 -

**[0012]** In another aspect, the invention provides a method of treating a CNS disorder in a subject in need thereof, wherein a symptom of the CNS disorder is axon degeneration within a CNS neuron. The method comprises administering to the subject an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote 5 regeneration of an axon in a CNS neuron affected by the CNS disorder. Following administration of the necrosis inhibitor and the apoptosis inhibitor, neural functions may be measured, for example, as an indication of axon regeneration. It is also contemplated that, following administration of the necrosis inhibitor and the apoptosis inhibitor, the neuron function of the CNS neuron is preserved or improved relative to the neuron function prior to 10 administration of the necrosis inhibitor and the apoptosis inhibitor. The CNS disorder includes, but is not limited to, brain injury, spinal cord injury, Alzheimer's disease, amyotrophic lateral sclerosis (ALS/Lou Gehrig's Disease), Parkinson's disease, multiple sclerosis, diabetic neuropathy, polyglutamine (polyQ) diseases, stroke, Fahr disease, Menke's disease, Wilson's disease, cerebral ischemia, and a prion disorder. In exemplary embodiments, the CNS disorder 15 is brain injury or spinal cord injury.

**[0013]** In another aspect, the invention provides a method of promoting neuron function following injury to a CNS neuron. The method comprises reducing the production and/or activity of a RIP-1 kinase and/or RIP-3 kinase in the CNS neuron thereby to promote CNS neuron function. In certain embodiments, the reduction in the production or activity of the 20 RIP-1 kinase and/or the RIP-3 kinase can be achieved by administering an effective amount of RIP kinase (RIPK) inhibitor, *e.g.*, a necrostatin. After treatment with the RIP kinase inhibitor, the CNS neuron may be capable of supporting axonal regeneration.

**[0014]** In another aspect, the invention provides a method of promoting axon regeneration in a CNS neuron, wherein the method comprises reducing the production and/or activity of a 25 RIP-1 kinase and/or a RIP-3 kinase in the CNS neuron thereby promoting axon regeneration in a CNS neuron. In certain embodiments, the reduction in the production or activity of the RIP-1 kinase and/or the RIP-3 kinase can be achieved by administering an effective amount of RIP kinase (RIPK) inhibitor, *e.g.*, a necrostatin.

**[0015]** In another aspect, the invention provides a composition for use in promoting axon 30 regeneration in a CNS neuron. The composition comprises a pharmaceutically acceptable carrier, a necrosis inhibitor and an apoptosis inhibitor.

- 5 -

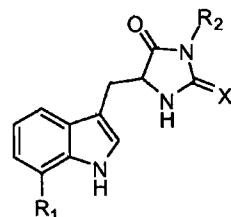
[0016] In each of the foregoing methods and compositions, the necrosis inhibitor can be a RIP kinase inhibitor, for example, a necrostatin. In certain embodiments of the foregoing methods, the necrostatin is necrostatin-1, necrostatin-2, necrostatin-3, necrostatin-4, necrostatin-5, necrostatin-7, or a combination thereof. In certain embodiments when a 5 necrostatin is administered, from about 0.05 mg to about 2 mg, 0.1 mg to about 1 mg, from about 0.2 mg to about 1 mg, or from about 0.2 mg to about 0.8 mg, of necrostatin can be administered.

[0017] In certain embodiments when a pan-caspase inhibitor is administered, from about 0.05 mg to about 1.5 mg, from about 0.15 mg to about 1.5 mg, from about 0.2 mg to about 1 10 mg, from about 0.2 mg to about 0.8 mg, from about 0.4 mg to about 1 mg, or from about 0.5 mg to about 0.8 mg, of the pan-caspase inhibitor can be administered. Exemplary pan-caspase inhibitors include zVAD, IDN-6556 or a combination thereof.

[0018] The necrosis inhibitor, *e.g.*, a necrostatin, and/or the apoptosis inhibitor may be administered locally. In other embodiments, the necrosis inhibitor, *e.g.*, a necrostatin, and/or 15 the apoptosis inhibitor may be administered systemically.

[0019] It is understood that the necrosis inhibitor, *e.g.*, a necrostatin, and/or the apoptosis inhibitor may be administered sequentially or simultaneously. The necrosis inhibitor, *e.g.*, a necrostatin, and the apoptosis inhibitor may be administered in the same or different carriers.

[0020] In each of the foregoing methods and compositions, the necrostatin can be selected 20 from one or more of the following necrostatins. For example, in certain embodiments, the necrostatin is a Nec-1 related compound of Formula I:



(I)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein  
25 X is O or S;

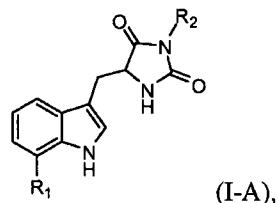
- 6 -

R<sub>1</sub> is hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, or halogen; and

R<sub>2</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl.

**[0021]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-A:

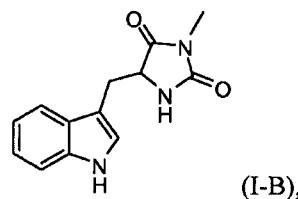
5



or a pharmaceutically acceptable salt, ester, or prodrug thereof, or optical isomers or racemic mixtures thereof, wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen and R<sub>2</sub> is H or an alkyl.

**[0022]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-B:

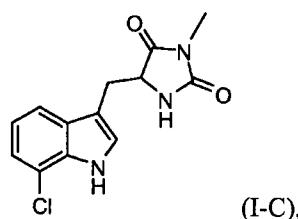
10



or a pharmaceutically acceptable salt, ester, or prodrug thereof.

**[0023]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-C:

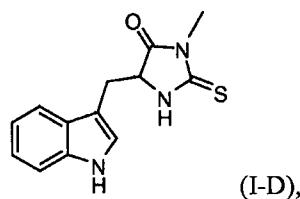
15



or a pharmaceutically acceptable salt, ester, or prodrug thereof.

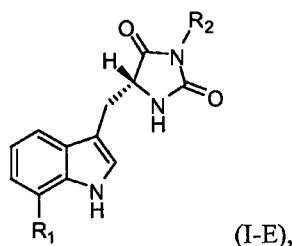
**[0024]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-D:

- 7 -



or a pharmaceutically acceptable salt, ester, or prodrug thereof.

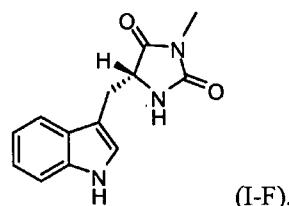
**[0025]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-E:



5

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen (for example, F, Cl, Br or I) and R<sub>2</sub> is H or an alkyl.

**[0026]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-F:

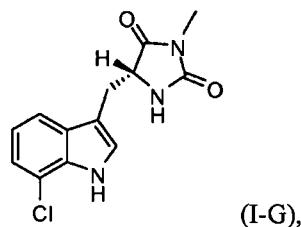


10

or a pharmaceutically acceptable salt, ester, or prodrug thereof.

**[0027]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-1 related compound of Formula I-G:

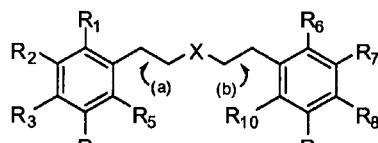
- 8 -



or a pharmaceutically acceptable salt, ester, or prodrug thereof.

**[0028]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-2 related compound of Formula II:

5



(II)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

X is -CH<sub>2</sub>-, -C(H)(R<sub>14</sub>)-, -C(=S)-, -C(=NH)-, or -C(O)-;

R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>4</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, R<sub>8</sub>, R<sub>9</sub>, and R<sub>10</sub> each represent independently hydrogen, acyl, acetyl, alkyl, halogen, amino, C<sub>1</sub>-C<sub>6</sub>alkoxyl, nitro, -C(O)R<sub>12</sub>, -C(S)R<sub>12</sub>, -C(O)OR<sub>12</sub>, -C(O)NR<sub>12</sub>R<sub>13</sub>, -C(S)NR<sub>12</sub>R<sub>13</sub>, or -S(O<sub>2</sub>)R<sub>12</sub>;

R<sub>11</sub> is hydrogen, acyl, acetyl, alkyl, or acylamino;

R<sub>12</sub> and R<sub>13</sub> each represent independently hydrogen, an optionally substituted alkyl, an optionally substituted aryl, an optionally substituted heteroaryl, an optionally substituted aralkyl, or an optionally substituted heteroaralkyl;

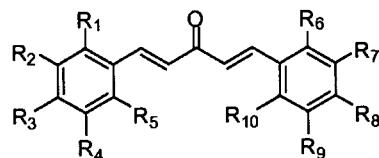
R<sub>14</sub> is acyl, acetyl, alkyl, halogen, amino, acylamino, nitro, -SR<sub>11</sub>, -N(R<sub>11</sub>)<sub>2</sub>, or -OR<sub>11</sub>;

the bond indicated by (a) can be a single or double bond; and

the bond indicated by (b) can be a single or double bond.

**[0029]** In each of the foregoing methods and compositions, the necrostatin can be a Nec-2 related compound of Formula IIA:

- 9 -



(II-A)

or a pharmaceutically acceptable salt thereof, wherein:

R<sub>1</sub>, R<sub>2</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, and R<sub>10</sub> each represent independently hydrogen, alkyl, halogen, 5 amino, or methoxyl; and  
 R<sub>3</sub>, R<sub>4</sub>, R<sub>8</sub>, and R<sub>9</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxy.

[0030] In each of the foregoing methods and compositions, the necrostatin can be a Nec-3 related compound of Formula III:



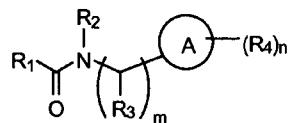
10 (III)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

Z is -CH<sub>2</sub>-, -CH<sub>2</sub>CH<sub>2</sub>-, -O-, -S-, -S(O)-, -S(O<sub>2</sub>)-, or -N(R<sub>7</sub>)-;  
 R<sub>1</sub>, R<sub>3</sub>, and R<sub>5</sub> each represent independently for each occurrence hydrogen, halogen, hydroxyl, amino, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkoxy, C<sub>1</sub>-C<sub>6</sub>alkoxy-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkanoyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfinyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfinyl-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl-C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, aralkyl, heterocycloalkyl, heteroaryl, or heteroaralkyl;  
 R<sub>2</sub> and R<sub>4</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxy;  
 R<sub>6</sub> is -C(O)R<sub>8</sub>, -C(S)R<sub>8</sub>, -C(O)OR<sub>8</sub>, -C(O)NR<sub>8</sub>R<sub>9</sub>, -C(S)NR<sub>8</sub>R<sub>9</sub>, -C(NH)R<sub>8</sub>, or -S(O<sub>2</sub>)R<sub>8</sub>;  
 R<sub>7</sub> is alkyl, aralkyl, or heteroaralkyl;  
 20 R<sub>8</sub> and R<sub>9</sub> each represent independently hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, heteroalkyl, aryl, heteroaryl, aralkyl, or heteroaralkyl; and  
 n represents independently for each occurrence 0, 1, or 2.

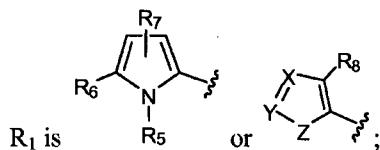
- 10 -

[0031] In each of the foregoing methods and compositions, the necrostatin can be a Nec-4 related compound of Formula IV:



(IV)

5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:



R<sub>2</sub> and R<sub>3</sub> each represent independently for each occurrence hydrogen or methyl;

R<sub>4</sub> represents independently for each occurrence halogen, hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>2</sub>-C<sub>6</sub>alkenyl, or C<sub>2</sub>-C<sub>4</sub>alkynyl;

10 R<sub>5</sub> is C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>6</sub> is hydrogen, halogen, or -CN;

R<sub>7</sub> is hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>8</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>8</sub> taken together with R<sub>9</sub>, when present, forms a carbocyclic ring;

R<sub>9</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>9</sub> taken together with R<sub>8</sub> forms a carbocyclic ring;

15 R<sub>10</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl;

A is phenylene or a 5-6 membered heteroarylene;

X is N or -C(R<sub>9</sub>)-;

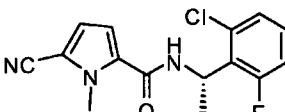
Y is N or -C(R<sub>10</sub>)-;

Z is S or O; and

20 m and n each represent independently 1, 2, or 3.

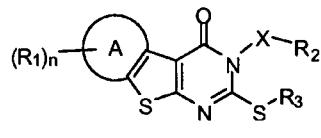
- 11 -

[0032] In each of the foregoing methods and compositions, the necrostatin can be a Nec-4

related compound of Formula IV-A:  or a pharmaceutically acceptable salt thereof.

[0033] In each of the foregoing methods and compositions, the necrostatin can be a Nec-5

5 related compound of Formula V:

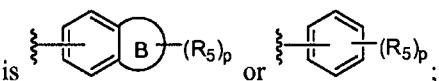


or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

A is a saturated or unsaturated 5-6 membered carbocyclic ring;

10 X is a bond or C<sub>1</sub>-C<sub>4</sub>alkylene;

R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

R<sub>2</sub> is 

R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN, -CN, C<sub>1</sub>-C<sub>6</sub>alkyl, or C<sub>2</sub>-C<sub>6</sub>alkenyl;

15 R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;

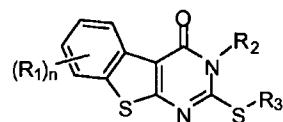
R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

B is a 5-6 membered heterocyclic or carbocyclic ring; and

n and p each represent independently 0, 1, or 2.

20 [0034] In each of the foregoing methods and compositions, the necrostatin can be a Nec-5 related compound of Formula V-A:

- 12 -



(V-A)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, or -N(R<sub>4</sub>)<sub>2</sub>;

5 R<sub>2</sub> is or ;

R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN;

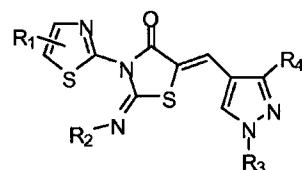
R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;

R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

10 B is a 5-6 membered heterocyclic or carbocyclic ring; and

n and p each represent independently 0, 1, or 2.

[0035] In each of the foregoing methods and compositions, the necrostatin can be a Nec-7 related compound of Formula VII:



15 (VII)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

R<sub>1</sub>, R<sub>2</sub>, and R<sub>3</sub> each represent independently hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>4</sub> is or ;

- 13 -

$R_5$  and  $R_6$  each represent independently for each occurrence halogen,  $C_1$ - $C_6$ alkyl, hydroxyl,  $C_1$ - $C_6$ alkoxyl,  $-N(R_7)_2$ ,  $-NO_2$ ,  $-S-C_1-C_6$ alkyl,  $-S$ -aryl,  $-SO_2-C_1-C_6$ alkyl,  $-SO_2$ -aryl,  $-C(O)R_7$ ,  $-CO_2R_7$ ,  $-C(O)N(R_7)_2$ , heterocycloalkyl, aryl, or heteroaryl;

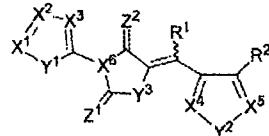
$R_7$  represents independently for each occurrence hydrogen,  $C_1$ - $C_6$ alkyl, aryl, or aralkyl;

5 or two occurrences of  $R_7$  attached to the same nitrogen atom are taken together with the nitrogen atom to which they are attached to form a 3-7 membered heterocyclic ring;

$A$  is a 5-6 membered heterocyclic ring; and

$p$  is 0, 1, or 2.

[0036] In each of the foregoing methods and compositions, the necrostatin can be a Nec-7  
10 related compound of Formula VIII:



(VIII)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

each  $X^1$ ,  $X^2$ ,  $X^3$ ,  $X^4$ ,  $X^5$ , and  $X^6$  is selected, independently, from N or  $CR^{X1}$ ;

15 each  $Y^1$ ,  $Y^2$ , and  $Y^3$  is selected, independently, from O, S,  $NR^{Y1}$ , or  $CR^{Y2}R^{Y3}$ ;

each  $Z^1$  and  $Z^2$  is selected, independently, from O, S, or  $NR^{Z1}$ ;

each  $R^{Y1}$  and  $R^{Z1}$  is selected, independently, from H, optionally substituted  $C_1$ -alkyl, optionally substituted  $C_2$ -alkenyl, optionally substituted  $C_2$ -alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, 20 optionally substituted heteroaryl,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ , or  $-C(=O)NR^{5A}R^{6A}$ ,

each  $R^{X1}$ ,  $R^{Y2}$ , and  $R^{Y3}$  is selected, independently, from H, halogen, CN, NC,  $NO_2$ ,  $N_3$ ,  $OR^3$ ,  $SR^3$ ,  $NR^3R^4$ ,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ ,  $-C(=O)NR^{5A}R^{6A}$ ,  $-S(=O)R^{5A}$ ,  $-S(=O)_2R^{5A}$ ,  $-S(=O)_2OR^{5A}$ ,  $-S(=O)_2NR^{5A}R^{6A}$ , optionally substituted  $C_1$ -alkyl, optionally substituted  $C_2$ -alkenyl, optionally substituted  $C_2$ -alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl;

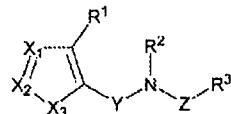
- 14 -

each  $R^1$ ,  $R^2$ ,  $R^{5A}$ ,  $R^{5B}$ ,  $R^{6A}$ , and  $R^{6B}$  is selected from H, optionally substituted  $C_{1-6}$  alkyl, optionally substituted  $C_{2-6}$  alkenyl, optionally substituted  $C_{2-6}$  alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl; or  $R^{5A}$  and  $R^{6A}$ , or  $R^{5B}$  and  $R^{6B}$  combine to form a heterocyclyl; and

5 each  $R^3$  and  $R^4$  is selected from H, optionally substituted  $C_{1-6}$  alkyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, optionally substituted heteroaryl,  $-C(=O)R^{5B}$ ,  $-C(=S)R^{5B}$ ,  $-C(=NR^{6B})R^{5B}$ ,  $-C(=O)OR^{5B}$ ,  $-C(=O)NR^{5B}R^{6B}$ ,  $-S(=O)R^{5B}$ ,  $-S(=O)_2R^{5B}$ ,  $-S(=O)OR^{5B}$ , or  $-S(=O)_2NR^{5B}R^{6B}$ . In certain embodiments when  $R^1$  is H,  $X^1$ ,  $X^2$ , and  $X^4$  are each  $CH$ ,  $X^3$ ,  $X^5$ , and  $X^6$  are each  $N$ ,  $Y^1$  and  $Y^3$  are each  $S$ ,  $Y^2$  is  $NH$ ,  $Z^1$  is  $NH$ , and  $Z^2$  is O, then  $R^2$  is not 4-fluorophenyl.

10

[0037] In each of the foregoing methods and compositions, the necrostatin can be a Nec-4 related compound of Formula IX:



(IX)

15 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

$X_1$  and  $X_2$  are, independently, N or  $CR^4$ ;

$X_3$  is selected from O, S,  $NR^5$ , or  $-(CR^5)_2$ ;

Y is selected from  $C(O)$  or  $CH_2$ ; and

Z is  $(CR^6R^7)_n$ ;

20  $R^1$  is selected from H, halogen, optionally substituted  $C_{1-6}$  alkyl, or optionally substituted  $C_{1-6}$  cycloalkyl, or optionally substituted aryl;

$R^2$  is selected from H or optionally substituted  $C_{1-6}$  alkyl;

$R^3$  is optionally substituted aryl;

each  $R^4$  is selected from H, halogen, carboxamido, nitro, cyano, optionally substituted

25  $C_{1-6}$  alkyl, or optionally substituted aryl;

- 15 -

$R^5$  is selected from H, halogen, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted aryl;

each  $R^6$  and  $R^7$  is, independently, selected from H, optionally substituted C<sub>1-6</sub>alkyl, or aryl; and

5         $n$  is 0, 1, 2, or 3. In certain embodiments, when  $X_1$  and  $X_2$  are N,  $X_3$  is S, Y is C(O), Z is CH<sub>2</sub>,  $R^2$  is H, and  $R^3$  is 2-chloro-6-fluoro-phenyl, then  $R^1$  is not methyl.

[0038]      The foregoing aspects and embodiments of the invention may be more fully understood by reference to the following figures, detailed description and claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0039]      The objects and features of the invention may be more fully understood by reference 10 to the drawings described herein.

[0040]      Figure 1 provides a schematic diagram showing proposed mechanisms of retinal ganglion cell death.

[0041]      Figures 2 provides a graph showing RGC survival in mice that were treated with ZVAD and/or Nec-1 following optic nerve crush injury.

15      [0042]      Figures 3A-E provide photographs showing axon regeneration in mice treated with ZVAD and/or Nec-1 following optic nerve crush injury. Figures 3A-E show longitudinal sections of the optic nerve stained with an antibody against  $\beta$ III-tubulin, following optic nerve crush injury. The vertical arrows denote the locations of the injury sites, and the horizontal reference lines denote regions where axon regeneration were detected following treatment with 20 Nec-1 and ZVAD (Figures 3D-E versus Figures 3A-C).

#### DETAILED DESCRIPTION

[0043]      The invention relates to methods for preserving neuron viability and/or promoting 25 axon regeneration and nerve function in a subject affected with a CNS disorder such as a traumatic CNS injury (e.g., traumatic brain injury or spinal cord injury) or a neurodegenerative disease (e.g., dementia, stroke, Alzheimer's disease, Parkinson's disease, and Huntington's disease). Using the methods described herein, it may be possible, for example, to reduce the loss of cognitive, sensory, and motor functions associated with the CNS disorder.

- 16 -

[0044] The invention is based, in part, on the discovery that a combination of a necrosis inhibitor (e.g., a RIPK inhibitor, e.g., a necrostatin) and an apoptosis inhibitor (e.g., a pan-caspase inhibitor, e.g., ZVAD or IDN-6556) induced axon regeneration in retinal ganglion cells (RGCs). Retinal ganglion cells (RGCs) are CNS neurons whose cell bodies reside in the retina and whose axons constitute the sole neuronal component of the optic nerve. It is thus contemplated that programmed necrosis may be a critical mechanism of neuronal cell death and axon degeneration in CNS disorders such as, for example, brain injury (e.g., traumatic brain injury), spinal cord injury, dementia, stroke, Alzheimer's disease, Parkinson's disease, and Huntington's disease. Without wishing to be bound by theory, but as depicted in Figure 1, 5 there are two proposed pathways for cell death (apoptosis and necrosis), in a retinal ganglion cell, which appear to be mediated by RIP-1, a serine/threonine kinase. RIP1 forms a death inducing signaling complex with Fas-associated domain (FADD) and caspase-8, thereby activating caspase-8 and the downstream cascade leading to apoptosis. On the other hand, 10 when caspase pathway is blocked (for example, with a caspase inhibitor such as ZVAD), RIP1 kinase is activated in a RIP1-RIP3 complex and promotes RGC necrosis. Thus, RIP Kinases 15 act as common intermediaries for various upstream death signals, and their blockade in addition to caspase inhibition provides effective neuroprotection.

[0045] The methods described herein are directed to therapies that target both the necrotic and apoptotic pathways of programmed cell death. In particular, the methods disclosed herein 20 facilitate a combination therapy where a necrosis inhibitor, e.g., a necrostatin (e.g., necrostatin-1 or necrostatin-4), can be administered either alone or in combination (either sequentially or simultaneously) with an apoptosis inhibitor e.g., a pan-caspase inhibitor (e.g., ZVAD or IDN-6556). In certain embodiments, the disclosed methods surprisingly use necrostatins at concentrations higher than those previously thought to be clinically tolerable. It is 25 contemplated that the combination of a necrostatin, e.g., necrostatin-1 or necrostatin-4, and a pan-caspase inhibitor, e.g., ZVAD or IDN-6556, produces a superior effect in promoting axon regeneration in a CNS neuron. It is further contemplated that the combination treatment of a necrostatin and a pan-caspase inhibitor preserves neuron viability and promotes nerve function in a CNS neuron following CNS injury.

30 [0046] Provided herein are methods for promoting neuron survival and axon regeneration in the CNS. CNS disorders characterized by impaired or failing axon growth or axon degeneration may arise from CNS neuron injury (e.g., trauma, surgery, nerve compression,

nerve contusion, nerve transection, neurotoxicity, or other physical injury to the brain or spinal cord) or neurodegenerative CNS disease, wherein a symptom of the disorder is axon degeneration (e.g., Alzheimer's disease, amyotrophic lateral sclerosis (ALS/Lou Gehrig's Disease), Parkinson's disease, multiple sclerosis, diabetic neuropathy, polyglutamine (polyQ) diseases, and stroke, Fahr disease, Menke's disease, Wilson's disease, cerebral ischemia, prion disorder (e.g., Creutzfeldt-Jakob disease). In an exemplary embodiment, the CNS disorder is brain injury (e.g., traumatic brain injury) or spinal cord injury (e.g., chronic, acute, or traumatic spinal cord injury). In another embodiment, the CNS disorder affects a subject's basic vital life functions such as breathing, heart beat and blood pressure, e.g., an injury to or aneurysm in the brain stem.

5 [0047] For convenience, certain terms in the specification, examples, and appended claims are collected in this section.

10 [0048] As used herein, "neuron," "neuronal cell" or "neural cell" refer to nerve cells, *i.e.*, cells that are responsible for conducting nerve impulses from one part of the body to another. 15 Most neurons consist of three distinct portions: a cell body, soma or perikaryon, which contains a nucleus and two kinds of cytoplasmic processes: dendrites and axons. Dendrites are usually highly branched, thick extensions of the cytoplasm of the cell body. An axon is usually a single long, thin process that is highly specialized and conducts nerve impulses away from the cell body to another neuron or muscular or glandular tissue. Along the length of an axon, there 20 may be side branches called "axon collaterals." Axon collaterals and axons may terminate by branching into many fine filaments called "axon terminals." The distal ends of axon terminals are called "synaptic end bulbs," which contain synaptic vesicles that store neurotransmitters. Axons may be surrounded by a multilayered, white, phospholipid, segmented covering called the myelin sheath. Axons containing such a covering are "myelinated."

25 [0049] As used herein, the term "cell death" is understood to mean the death of a cell, for example, by apoptosis or necrosis.

30 [0050] As used herein, the term "apoptosis" is understood to mean caspase-dependent cell death, which is characterized by any of the following properties: cell shrinkage, nuclear condensation, DNA fragmentation or membrane blebbing.

35 [0051] As used herein, the term "apoptosis inhibitor" is understood to mean any agent that, when administered to a mammal, reduces apoptotic cell death in a cell. For example, it is

understood that certain useful apoptosis inhibitors act by reducing or eliminating the activity of one or more members of the intrinsic or extrinsic or common apoptotic pathways.

Furthermore, it is understood that an agent that either directly or indirectly affects the activity of one or more caspases (e.g., a pan-caspase inhibitor) is considered to be an apoptosis

5 inhibitor. It is understood that a caspase inhibitor can affect the activity of a caspase either directly by modulating a specific caspase in the apoptotic pathway or indirectly by modulating a downstream caspase present in the apoptotic pathway.

**[0052]** As used herein, the term “pan-caspase inhibitor” is understood to mean a broad-spectrum caspase inhibitor that inhibits at least two, preferably at least three different caspases

10 (e.g., caspase-1, caspase-2, caspase-3, caspase-4, caspase-5, caspase-6, caspase-7, caspase-8, caspase-9, caspase-10, caspase-11, caspase-12, caspase-13, and/or caspase-14. ZVAD (also known as Z-VAD, Benzyloxycarbonyl-Val-Ala-Asp(OMe)-fluoromethylketone and carbobenzoxy-valyl-alanyl-aspartyl-[O-methyl]- fluoromethylketone) is an exemplary pan-caspase inhibitor and is available from R&D Systems (Cat. No. FMK001) and Promega (Cat.

15 No. G7231). Other exemplary pan-caspase inhibitors that may be used include IDN-6556 (also known as “PF-3,491,390”) available from Conatus Pharmaceuticals, Inc. (formerly Idun Pharmaceuticals, Inc.), VX-799 available from Vertex Pharmaceuticals, Inc., MX1013 available Maxim Pharmaceuticals, Inc., Xyz033mp available from LG Chemical, Inc., all of which are described, for example, in Linton, S.D. (2005) CURRENT TOPICS IN MEDICAL CHEM.

20 5:1697-1717. It is understood that a “pan-caspase inhibitor” may also be a cocktail (e.g., a combination) of caspase inhibitors including two or more of specific caspase inhibitors (e.g., synthetic or endogenous caspase inhibitors).

**[0053]** As used herein, the term “necrosis” is understood to mean caspase-independent cell death characterized by any of the following properties: cellular and/or organelle swelling,

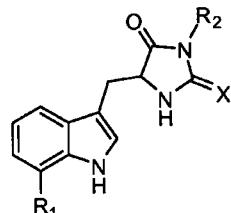
25 plasma membrane rupture, or discontinuity in plasma, nuclear and/or organelle membranes. As used herein, the terms “necroptosis” and “programmed necrosis” refer to a form of necrosis and is understood to mean one form of programmed or regulated necrosis, and in certain embodiments, necroptosis is mediated by the serine/threonine kinase activity of receptor interacting protein (RIP) kinases, for example, RIP-1 kinase and/or RIP-3 kinase.

30 **[0054]** As used herein, the term “necrosis inhibitor” is understood to mean an agent, which, when administered to a mammal, reduces necrotic cell death in a cell. For example, it is

understood that certain necrosis inhibitors act by reducing or inhibiting necroptosis or programmed necrosis. A necrosis inhibitor can be an agent that modulates the production and/or activity of one or more RIP kinases (e.g., RIP-1 kinase and/or RIP-3 kinase). For example, an inhibitor of RIP-1 kinase is understood to modulate the activity of RIP-1 kinase as well as downstream RIP kinases, e.g., RIP-3 kinase, in the necrosis cascade. Accordingly, a RIP-1 kinase inhibitor is also understood to modulate RIP-3 kinase activity.

5 [0055] As used herein, the term “necrostatin” or “nec” is understood to mean an inhibitor of caspase-independent cell death or necroptosis. Exemplary necrostatins include necrostatin-1 (“Nec-1”), necrostatin-2 (“Nec-2”), necrostatin-3 (“Nec-3”), necrostatin-4 (“Nec-4”),  
10 necrostatin-5 (“Nec-5”) and necrostatin-7 (“Nec-7”).

[0056] In certain embodiments, the necrostatin is a Nec-1 related compound of Formula I:



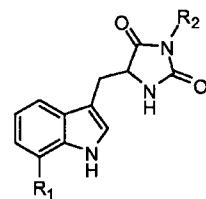
(I)

15 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein  
X is O or S;  
R<sub>1</sub> is hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, or halogen; and  
R<sub>2</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl.

[0057] In certain embodiments, X is O. In certain embodiments, R<sub>1</sub> is hydrogen or halogen (such as chlorine). In certain embodiments, R<sub>2</sub> is a methyl or ethyl. In certain other  
20 embodiments, R<sub>1</sub> is hydrogen or Cl, and R<sub>2</sub> is a methyl.

[0058] In certain embodiments, the necrostatin is a Nec-1 related compound of Formula I-A, shown below:

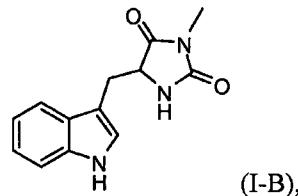
- 20 -



(I-A)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, or optical isomers or racemic mixtures thereof, wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen (for example, F, Cl, Br or I) and 5 R<sub>2</sub> is H or an alkyl. In certain embodiments, R<sub>1</sub> is H or Cl. In certain other embodiments, R<sub>2</sub> is a methyl or ethyl. In certain other embodiments, R<sub>1</sub> is H or Cl, and R<sub>2</sub> is a methyl.

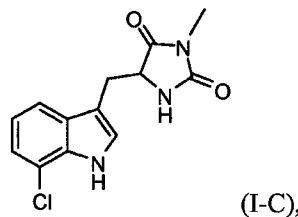
[0059] In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-B, shown below:



(I-B),

10 or a pharmaceutically acceptable salt, ester, or prodrug thereof.

[0060] In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-C, shown below:

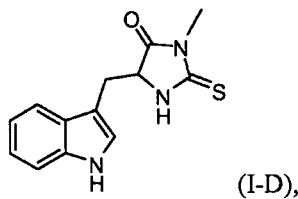


(I-C),

or a pharmaceutically acceptable salt, ester, or prodrug thereof.

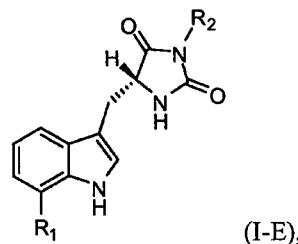
15 [0061] In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-D, shown below:

- 21 -



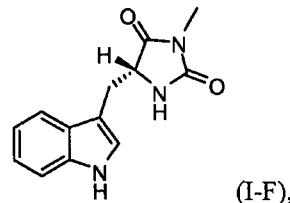
or a pharmaceutically acceptable salt, ester, or prodrug thereof.

**[0062]** In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-E, shown below:



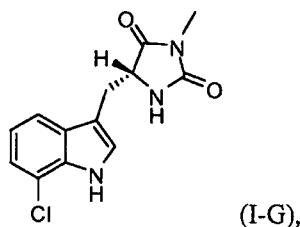
or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen (for example, F, Cl, Br or I) and R<sub>2</sub> is H or an alkyl. In certain embodiments, R<sub>1</sub> is H or Cl. In certain other embodiments, R<sub>2</sub> is a methyl or ethyl. In certain other embodiments, R<sub>1</sub> is H or Cl, and R<sub>2</sub> is a methyl.

**10 [0063]** In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-F, shown below:



or a pharmaceutically acceptable salt, ester, or prodrug thereof. In certain other embodiments, the necrostatin is a Nec-1 related compound of Formula I-G, shown below:

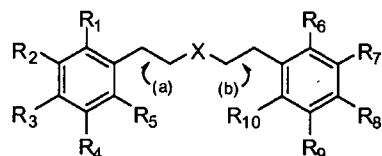
- 22 -



or a pharmaceutically acceptable salt, ester, or prodrug thereof.

**[0064]** The Nec-1 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in Degterev *et al.*, in *Nature Chemical Biology*, 5 (2005), vol. 1, 112-119; Degterev *et al.*, in *Nature Chemical Biology*, (2008), vol. 4, 313-321; and International Patent Application Publication No. WO 2007/075772, all of which are hereby incorporated by reference.

**[0065]** In certain embodiments, the necrostatin is a Nec-2 related compound of Formula II:



10 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

X is -CH<sub>2</sub>-, -C(H)(R<sub>14</sub>)-, -C(=S)-, -C(=NH)-, or -C(O)-;

15 R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>4</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, R<sub>8</sub>, R<sub>9</sub>, and R<sub>10</sub> each represent independently hydrogen, acyl, acetyl, alkyl, halogen, amino, C<sub>1</sub>-C<sub>6</sub>alkoxyl, nitro, -C(O)R<sub>12</sub>, -C(S)R<sub>12</sub>, -C(O)OR<sub>12</sub>, -C(O)NR<sub>12</sub>R<sub>13</sub>, -C(S)NR<sub>12</sub>R<sub>13</sub>, or -S(O<sub>2</sub>)R<sub>12</sub>;

R<sub>11</sub> is hydrogen, acyl, acetyl, alkyl, or acylamino;

R<sub>12</sub> and R<sub>13</sub> each represent independently hydrogen, an optionally substituted alkyl, an optionally substituted aryl, an optionally substituted heteroaryl, an optionally substituted aralkyl, or an optionally substituted heteroaralkyl;

20 R<sub>14</sub> is acyl, acetyl, alkyl, halogen, amino, acylamino, nitro, -SR<sub>11</sub>, -N(R<sub>11</sub>)<sub>2</sub>, or -OR<sub>11</sub>; the bond indicated by (a) can be a single or double bond; and

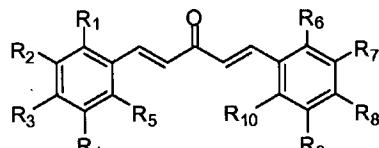
- 23 -

the bond indicated by (b) can be a single or double bond.

**[0066]** In certain embodiments, X is -C(O)-. In certain embodiments, R<sub>1</sub>, R<sub>2</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, and R<sub>10</sub> each represent independently hydrogen, acyl, alkyl, halogen, or amino. In certain embodiments, R<sub>3</sub>, R<sub>4</sub>, R<sub>8</sub>, and R<sub>9</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxyl. In certain embodiments, the bond indicated by (a) is a double bond; and the bond indicated by (b) is a double bond. In certain embodiments, when each of R<sub>1</sub>, R<sub>4</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>9</sub> and R<sub>10</sub> is hydrogen and each of R<sub>2</sub>, R<sub>3</sub>, R<sub>7</sub>, and R<sub>8</sub> is methoxyl, then X is not -C(O)-, -CH<sub>2</sub>-, or -CH(OH)-.

**[0067]** In certain other embodiments, the necrostatin is a Nec-2 related compound of Formula II-A:

10



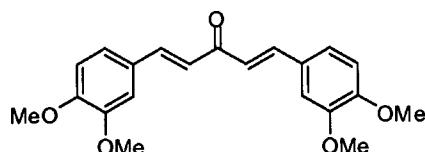
(II-A)

or a pharmaceutically acceptable salt thereof, wherein:

R<sub>1</sub>, R<sub>2</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, and R<sub>10</sub> each represent independently hydrogen, alkyl, halogen, amino, or methoxyl; and

15 R<sub>3</sub>, R<sub>4</sub>, R<sub>8</sub>, and R<sub>9</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxyl.

**[0068]** In certain other embodiments, the Nec-2 related compound is



or a pharmaceutically acceptable salt thereof.

**[0069]** The Nec-2 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in International Patent Application Publication No. WO 2007/075772, which is hereby incorporated by reference.

**[0070]** In certain embodiments, the necrostatin is a Nec-3 related compound of Formula III:

- 24 -



(III)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

Z is -CH<sub>2</sub>-, -CH<sub>2</sub>CH<sub>2</sub>-, -O-, -S-, -S(O)-, -S(O<sub>2</sub>)-, or -N(R<sub>7</sub>)-;

5 R<sub>1</sub>, R<sub>3</sub>, and R<sub>5</sub> each represent independently for each occurrence hydrogen, halogen, hydroxyl, amino, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkoxy, C<sub>1</sub>-C<sub>6</sub>alkoxy-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkanoyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfinyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfinyl-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl-C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, aralkyl, heterocycloalkyl, heteroaryl, or heteroaralkyl;

R<sub>2</sub> and R<sub>4</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxy;

10 R<sub>6</sub> is -C(O)R<sub>8</sub>, -C(S)R<sub>8</sub>, -C(O)OR<sub>8</sub>, -C(O)NR<sub>8</sub>R<sub>9</sub>, -C(S)NR<sub>8</sub>R<sub>9</sub>, -C(NH)R<sub>8</sub>, or -S(O<sub>2</sub>)R<sub>8</sub>;

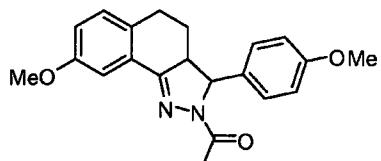
R<sub>7</sub> is alkyl, aralkyl, or heteroaralkyl;

R<sub>8</sub> and R<sub>9</sub> each represent independently hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, heteroalkyl, aryl, heteroaryl, aralkyl, or heteroaralkyl; and

n represents independently for each occurrence 0, 1, or 2.

15 [0071] In certain embodiments, Z is -CH<sub>2</sub>-. In certain embodiments, R<sub>1</sub>, R<sub>3</sub>, and R<sub>5</sub> each represent independently for each occurrence hydrogen, halogen, hydroxyl, amino, or C<sub>1</sub>-C<sub>6</sub>alkyl. In certain embodiments, R<sub>2</sub> and R<sub>4</sub> are methoxy. In certain embodiments, R<sub>6</sub> is C(O)R<sub>8</sub>, and R<sub>8</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl. In certain embodiments, R<sub>7</sub> is alkyl. In certain embodiments, R<sub>8</sub> and R<sub>9</sub> each represent independently hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl. In certain embodiments, n is 0.

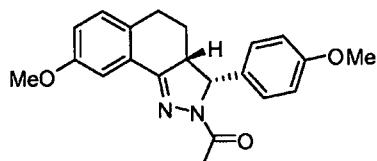
20 [0072] In certain embodiments, the Nec-3 related compound is



or a pharmaceutically acceptable salt thereof.

- 25 -

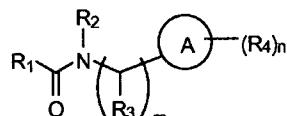
[0073] In certain other embodiments, the Nec-3 related compound is



or a pharmaceutically acceptable salt thereof.

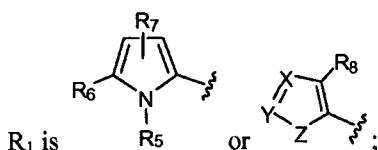
[0074] The Nec-3 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in Degterev *et al.*, in *Nature Chemical Biology*, 5 (2008), vol. 4, 313-321; and International Patent Application Publication No. WO 2007/075772, both of which is hereby incorporated by reference.

[0075] In certain embodiments, the necrostatin is a Nec-4 related compound of Formula IV:



(IV)

10 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:



R<sub>2</sub> and R<sub>3</sub> each represent independently for each occurrence hydrogen or methyl;

R<sub>4</sub> represents independently for each occurrence halogen, hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>2</sub>-C<sub>6</sub>alkenyl, or C<sub>2</sub>-C<sub>4</sub>alkynyl;

15 R<sub>5</sub> is C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>6</sub> is hydrogen, halogen, or -CN;

R<sub>7</sub> is hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>8</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>8</sub> taken together with R<sub>9</sub>, when present, forms a carbocyclic ring;

R<sub>9</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>9</sub> taken together with R<sub>8</sub> forms a carbocyclic ring;

20 R<sub>10</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl;

- 26 -

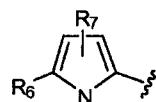
A is phenylene or a 5-6 membered heteroarylene;

X is N or -C(R<sub>9</sub>)-;

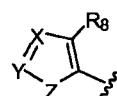
Y is N or -C(R<sub>10</sub>)-;

Z is S or O; and

5 m and n each represent independently 1, 2, or 3.

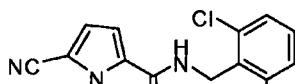


[0076] In certain embodiments, R<sub>1</sub> is



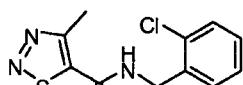
10 In certain embodiments, R<sub>2</sub> is hydrogen. In certain embodiments, R<sub>3</sub> is methyl. In certain other embodiments, R<sub>3</sub> is hydrogen. In certain embodiments, R<sub>4</sub> is halogen, such as fluorine or chlorine. In certain embodiments, R<sub>4</sub> is halogen. In certain embodiments, R<sub>5</sub> is methyl or ethyl. In certain embodiments, R<sub>6</sub> is -CN. In certain embodiments, A is phenylene. In certain embodiments, X is N. In certain embodiments, Y is N. In certain embodiments, Z is S. In certain embodiments, A is phenylene. In certain embodiments, R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, such as methyl. In certain embodiments, m is 1. In certain embodiments, n is 2.

[0077] In certain embodiments, the necrostatin is a Nec-4 related compound of Formula



15 IV-A: or a pharmaceutically acceptable salt thereof.

[0078] In certain embodiments, the necrostatin is a Nec-4 related compound of Formula

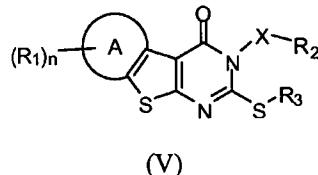


IV-B: or a pharmaceutically acceptable salt thereof.

[0079] The Nec-4 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in Teng *et al.*, (2007) BIOORG MED CHEM LETT, 17: 6836-6840; and Teng *et al.*, (2008) BIOORG MED CHEM LETT, 18: 3219-3223, both of which are incorporated herein by reference.

- 27 -

[0080] In certain embodiments, the necrostatin is a Nec-5 related compound of Formula V:



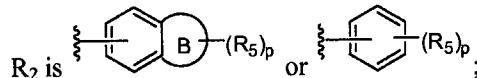
or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

5 A is a saturated or unsaturated 5-6 membered carbocyclic ring;

X is a bond or C<sub>1</sub>-C<sub>4</sub>alkylene;

R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or

C(O)N(R<sub>4</sub>)<sub>2</sub>;



10 R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN, -CN, C<sub>1</sub>-C<sub>6</sub>alkyl, or C<sub>2</sub>-C<sub>6</sub>alkenyl;

R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;

R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

B is a 5-6 membered heterocyclic or carbocyclic ring; and

15 n and p each represent independently 0, 1, or 2.

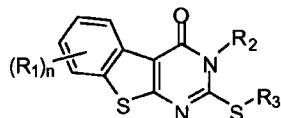
[0081] In certain embodiments, X is a bond. In certain embodiments, A is an unsaturated 6-membered carbocyclic ring. In certain embodiments, R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, or

C<sub>1</sub>-C<sub>6</sub>alkoxyl. In certain embodiments, R<sub>2</sub> is such as . In certain embodiments, R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN, such as -CH<sub>2</sub>-CN. In certain embodiments, R<sub>4</sub> represents independently for each occurrence hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl. In certain embodiments, R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, or C<sub>1</sub>-C<sub>6</sub>alkoxyl. In certain embodiments, B is a 5-6 membered heterocyclic ring. In certain embodiments, n is 0. In certain embodiments, p is 0.

[0082] In certain embodiments, the necrostatin is a Nec-5 related compound

- 28 -

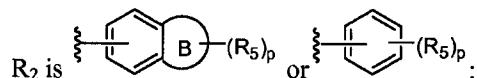
of Formula V-A:



(V-A)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

5 R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, or -N(R<sub>4</sub>)<sub>2</sub>;



R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN;

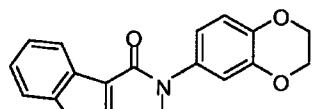
R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;

R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-

10 C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

B is a 5-6 membered heterocyclic or carbocyclic ring; and

n and p each represent independently 0, 1, or 2.



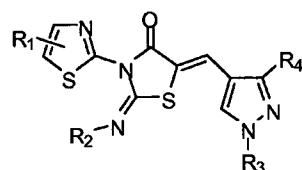
[0083] In certain embodiments, the Nec-5 compound is or a pharmaceutically acceptable salt thereof.

15 [0084] The Nec-5 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in Degterev *et al.*, in *Nature Chemical Biology*, (2008), vol. 4, 313-321; and International Patent Application Publication No. WO 2008/045406, both of which is hereby incorporated by reference.

[0085] In certain embodiments, the necrostatin is a Nec-7 related compound of Formula

20 VII:

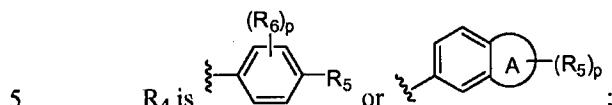
- 29 -



(VII)

or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

R<sub>1</sub>, R<sub>2</sub>, and R<sub>3</sub> each represent independently hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;



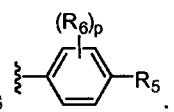
R<sub>5</sub> and R<sub>6</sub> each represent independently for each occurrence halogen, C<sub>1</sub>-C<sub>6</sub>alkyl, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>7</sub>)<sub>2</sub>, -NO<sub>2</sub>, -S-C<sub>1</sub>-C<sub>6</sub>alkyl, -S-aryl, -SO<sub>2</sub>-C<sub>1</sub>-C<sub>6</sub>alkyl, -SO<sub>2</sub>-aryl, -C(O)R<sub>7</sub>, -CO<sub>2</sub>R<sub>7</sub>, -C(O)N(R<sub>7</sub>)<sub>2</sub>, heterocycloalkyl, aryl, or heteroaryl;

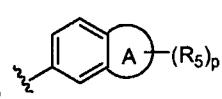
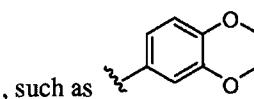
10 R<sub>7</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl; or two occurrences of R<sub>7</sub> attached to the same nitrogen atom are taken together with the nitrogen atom to which they are attached to form a 3-7 membered heterocyclic ring;

A is a 5-6 membered heterocyclic ring; and

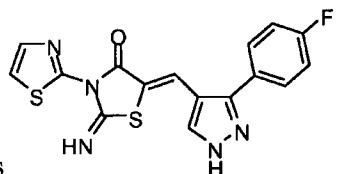
p is 0, 1, or 2.

[0086] In certain embodiments, R<sub>1</sub> is hydrogen. In certain embodiments, R<sub>2</sub> is hydrogen.

15 In certain embodiments, R<sub>3</sub> is hydrogen. In certain embodiments, R<sub>4</sub> is . In certain embodiments, R<sub>5</sub> is halogen, C<sub>1</sub>-C<sub>6</sub>alkyl, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, or -N(R<sub>7</sub>)<sub>2</sub>. In certain other embodiments, R<sub>5</sub> is halogen, such as fluorine or chlorine. In certain embodiments, p is 0.

In certain other embodiments, R<sub>4</sub> is , such as . In certain

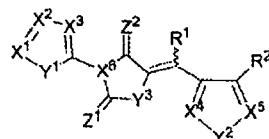
- 30 -



embodiments, the Nec-7 related compound is , or a pharmaceutically acceptable salt thereof.

**[0087]** The Nec-7 related compounds described above can be prepared based on synthetic procedures described in the literature, such as in Zheng *et al.*, in BIOORG MED CHEM LETT, 5 2008, vol. 18, 4932-4935, which is incorporated herein by reference.

**[0088]** In certain embodiments, the necrostatin is a Nec-7 related compound of Formula VIII:



(VIII)

10 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

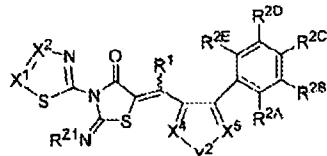
- each  $X^1, X^2, X^3, X^4, X^5$ , and  $X^6$  is selected, independently, from N or  $CR^{X1}$ ;
- each  $Y^1, Y^2$ , and  $Y^3$  is selected, independently, from O, S,  $NR^{Y1}$ , or  $CR^{Y2}R^{Y3}$ ;
- each  $Z^1$  and  $Z^2$  is selected, independently, from O, S, or  $NR^{Z1}$ ;
- each  $R^{Y1}$  and  $R^{Z1}$  is selected, independently, from H, optionally substituted C<sub>1</sub>-alkyl, optionally substituted C<sub>2</sub>-alkenyl, optionally substituted C<sub>2</sub>-alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, optionally substituted heteroaryl,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ , or  $-C(=O)NR^{5A}R^{6A}$ ;
- each  $R^{X1}, R^{Y2}$ , and  $R^{Y3}$  is selected, independently, from H, halogen, CN, NC,  $NO_2$ ,  $N_3$ ,  $OR^3$ ,  $SR^3$ ,  $NR^3R^4$ ,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ ,  $-C(=O)NR^{5A}R^{6A}$ ,  $-S(=O)R^{5A}$ ,  $-S(=O)_2R^{5A}$ ,  $-S(=O)_2OR^{5A}$ ,  $-S(=O)_2NR^{5A}R^{6A}$ , optionally substituted C<sub>1</sub>-alkyl, optionally substituted C<sub>2</sub>-alkenyl, optionally substituted C<sub>2</sub>-alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl;

- 31 -

each  $R^1$ ,  $R^2$ ,  $R^{5A}$ ,  $R^{5B}$ ,  $R^{6A}$ , and  $R^{6B}$  is selected from H, optionally substituted  $C_{1-6}$  alkyl, optionally substituted  $C_{2-6}$  alkenyl, optionally substituted  $C_{2-6}$  alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl; or  $R^{5A}$  and  $R^{6A}$ , or  $R^{5B}$  and  $R^{6B}$  combine to form a heterocyclyl; and

5 each  $R^3$  and  $R^4$  is selected from H, optionally substituted  $C_{1-6}$  alkyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, optionally substituted heteroaryl,  $-C(=O)R^{5B}$ ,  $-C(=S)R^{5B}$ ,  $-C(=NR^{6B})R^{5B}$ ,  $-C(=O)OR^{5B}$ ,  $-C(=O)NR^{5B}R^{6B}$ ,  $-S(=O)R^{5B}$ ,  $-S(=O)_2R^{5B}$ ,  $-S(=O)_2OR^{5B}$ , or  $-S(=O)_2NR^{5B}R^{6B}$ . In certain  
 10 embodiments, when  $R^1$  is H,  $X^1$ ,  $X^2$ , and  $X^4$  are each  $CH$ ,  $X^3$ ,  $X^5$ , and  $X^6$  are each N,  $Y^1$  and  $Y^3$  are each S,  $Y^2$  is NH,  $Z^1$  is NH, and  $Z^2$  is O, then  $R^2$  is not 4-fluorophenyl.

[0089] In certain embodiments, the necrostatin is a Nec-7 related compound of Formula VIII-A:



(VIII-A)

15 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

$X^1, X^2, X^4, X^5, R^1, Y^2$ , and  $R^{Z1}$  are as defined for Formula (VIII);

each  $R^{2A}$ ,  $R^{2B}$ ,  $R^{2C}$ ,  $R^{2D}$ , and  $R^{2E}$  is selected, independently, from H, halogen, optionally substituted  $C_{1-6}$  alkyl, optionally substituted  $C_{2-6}$  alkenyl, optionally substituted  $C_{2-6}$  alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted 20 aryl, optionally substituted heteroaryl, CN, NC,  $NO_2$ ,  $N_3$ ,  $OR^7$ ,  $SR^7$ ,  $S(=O)R^{12}$ ,  $S(=O)_2R^{12}$ ,  $S(=O)OR^{12}$ ,  $S(=O)_2OR^{12}$ ,  $NR^7R^8$ ,  $C(=O)R^{12}$ ,  $C(=O)OR^{12}$ ,  $C(=O)NR^{12}R^{13}$ ,  $C(=S)R^{12}$ ,  $C(=S)OR^{12}$ ,  $C(=S)NR^{12}R^{13}$ ,  $C(=NR^9)R^{12}$ ,  $C(=NR^9)OR^{12}$ , or  $C(=NR^9)NR^{12}R^{13}$ , or  $R^{2A}$  and  $R^{2B}$ ,  $R^{2B}$  and  $R^{2C}$ ,  $R^{2C}$  and  $R^{2D}$ , or  $R^{2D}$  and  $R^{2E}$  combine to form an optionally substituted cycloalkyl or an optionally substituted heterocyclyl;

25 each R<sup>7</sup>, R<sup>8</sup>, and R<sup>9</sup> is selected, independently, from H, optionally substituted C<sub>1-6</sub> alkyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, optionally substituted heieroaryl, S(=O)R<sup>10</sup>, S(=O)<sub>2</sub>R<sup>10</sup>, C(=O)R<sup>10</sup>, C(=O)OR<sup>10</sup>,

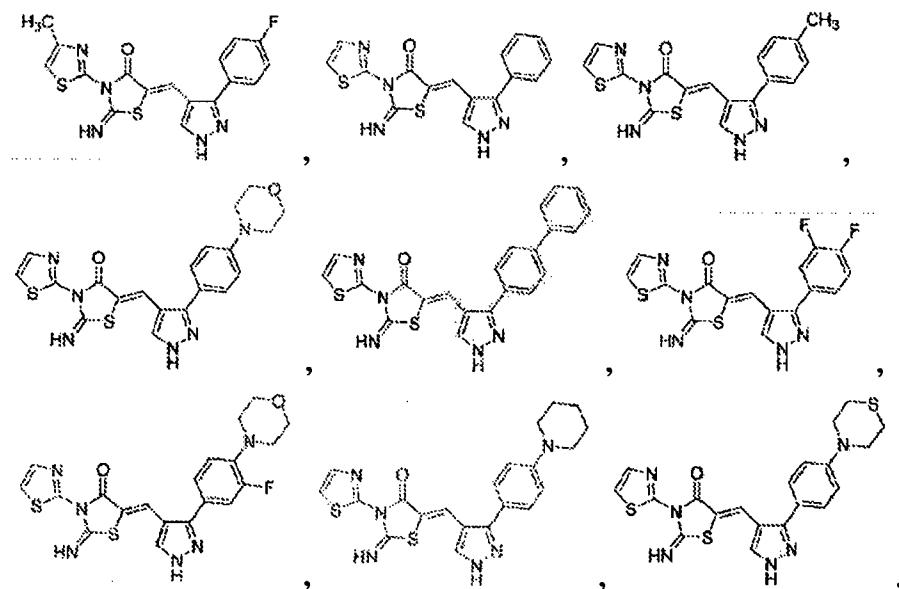
- 32 -

$C(=O)NR^{10}R^{11}$ ,  $C(=S)R^{10}$ ,  $C(=S)OR^{10}$ ,  $C(=S)NR^{10}R^{11}$ ,  $C(=NR^{14})R^{10}$ ,  $C(=NR^{14})OR^{10}$ , or  $C(=NR^{14})NR^{10}R^{11}$ , or  $R^7$  and  $R^8$  combine to form an optionally substituted heterocyclyl; and

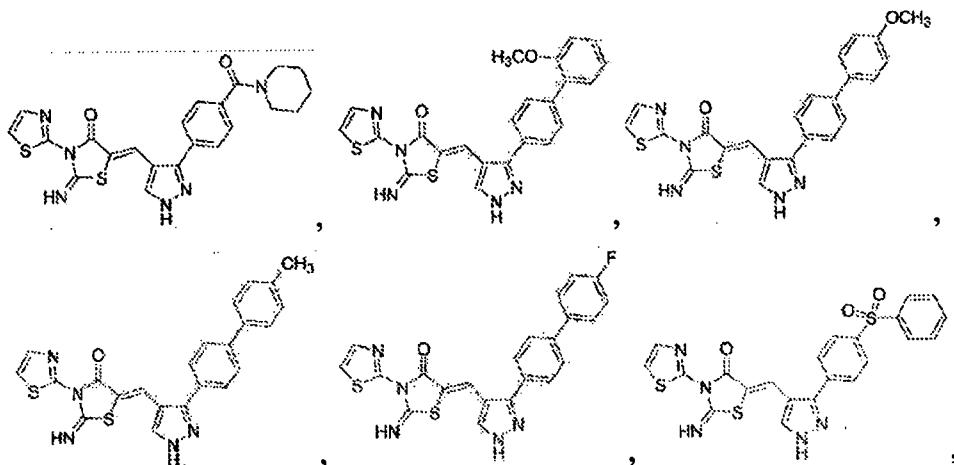
each  $R^{10}$ ,  $R^{11}$ ,  $R^{12}$ ,  $R^{13}$ , and  $R^{14}$  is selected, independently, from H, optionally substituted  $C_{1-6}$ alkyl, optionally substituted  $C_{2-6}$ alkenyl, optionally substituted  $C_{2-6}$ alkynyl, optionally substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl, or  $R^{10}$  and  $R^{11}$  or  $R^{12}$  and  $R^{13}$  combine to form an optionally substituted heterocyclyl.

[0090] In certain embodiments, each  $R^{2A}$ ,  $R^{2B}$ ,  $R^{2C}$ ,  $R^{2D}$ , and  $R^{2E}$  is selected, independently, from H, halogen,  $C_{1-6}$ alkyl,  $C_{2-6}$ alkenyl,  $C_{2-6}$ alkynyl, cycloalkyl, heterocyclyl, aryl, or heteroaryl.

[0091] In certain embodiments, the necrostatin is a Nec-7 related compound selected from:



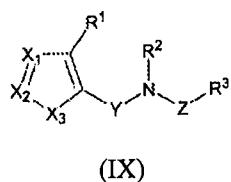
- 33 -



and pharmaceutically acceptable salts thereof.

**[0092]** The Nec-7 related compounds described above can be prepared based on synthetic procedures described in the literature, such as International Patent Application Publication No. WO 2010/075290, which is hereby incorporated by reference.

**[0093]** In certain embodiments, the necrostatin is a Nec-4 related compound of Formula IX:



10 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

X<sub>1</sub> and X<sub>2</sub> are, independently, N or CR<sup>4</sup>;

X<sub>3</sub> is selected from O, S, NR<sup>5</sup>, or —(CR<sup>5</sup>)<sub>2</sub>;

Y is selected from C(O) or CH<sub>2</sub>; and

Z is (CR<sup>6</sup>R<sup>7</sup>)<sub>n</sub>;

15 R<sup>1</sup> is selected from H, halogen, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted C<sub>1-6</sub>cycloalkyl, or optionally substituted aryl;

R<sup>2</sup> is selected from H or optionally substituted C<sub>1-6</sub>alkyl;

R<sup>3</sup> is optionally substituted aryl;

- 34 -

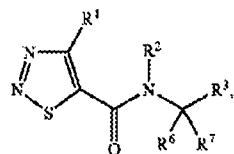
each R<sup>4</sup> is selected from H, halogen, carboxamido, nitro, cyano, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted aryl;

R<sup>5</sup> is selected from H, halogen, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted aryl;

5 each R<sup>6</sup> and R<sup>7</sup> is, independently, selected from H, optionally substituted C<sub>1-6</sub>alkyl, or aryl; and

n is 0, 1, 2, or 3. In certain embodiments, when X<sub>1</sub> and X<sub>2</sub> are N, X<sub>3</sub> is S, Y is C(O), Z is CH<sub>2</sub>, R<sup>2</sup> is H, and R<sup>3</sup> is 2-chloro-6-fluoro-phenyl, then R<sup>1</sup> is not methyl.

[0094] In certain embodiments, the necrostatin is a Nec-4 related compound of Formula 10 IX-A:

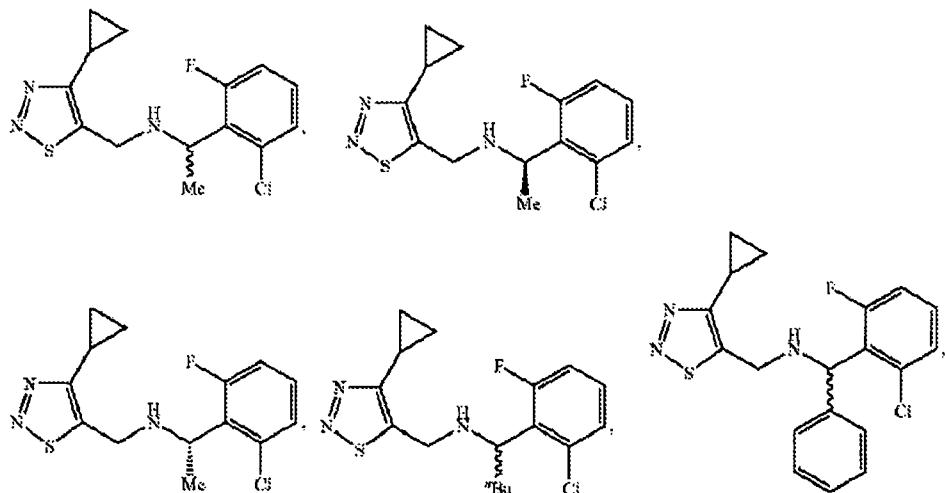


(IX-A)

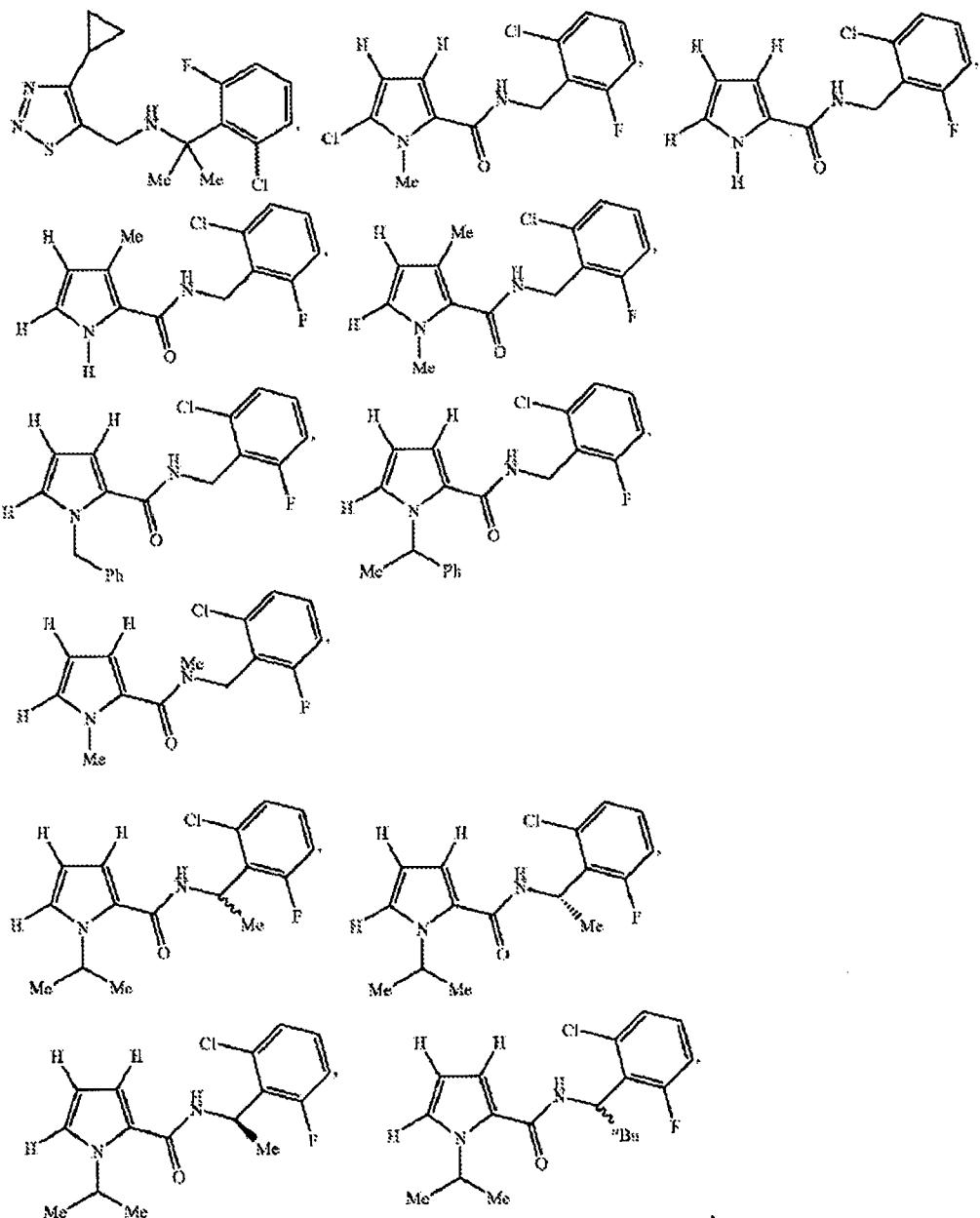
or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

R<sup>1</sup>, R<sup>2</sup>, R<sup>3</sup>, R<sup>6</sup> and R<sup>7</sup> are as defined in Formula (IX).

15 [0095] In certain embodiments, the necrostatin is a Nec-4 related compound selected from:



- 35 -



and pharmaceutically acceptable salts thereof.

**[0096]** The Nec-4 related compounds described above can be prepared based on synthetic procedures described in the literature, such as U.S. Patent Application Publication No.

10 2009/0099242, which is hereby incorporated by reference.

[0097] The term "alkyl" is art-recognized, and includes saturated aliphatic groups, including straight-chain alkyl groups, branched-chain alkyl groups, cycloalkyl (alicyclic) groups, alkyl substituted cycloalkyl groups, and cycloalkyl substituted alkyl groups. In certain embodiments, a straight chain or branched chain alkyl has about 10 or fewer carbon atoms in 5 its backbone (e.g., C<sub>1</sub>-C<sub>10</sub> for straight chain, C<sub>3</sub>-C<sub>10</sub> for branched chain), and alternatively, 5, 4, 3, 2 or 1 carbon atoms in its backbone. Likewise, cycloalkyls have from about 3 to about 10 carbon atoms in their ring structure, and alternatively about 5, 6 or 7 carbons in the ring structure. Exemplary alkyl groups include methyl, ethyl, n-propyl, isopropyl, n-butyl, sec-butyl, isobutyl, tert-butyl, cyclopropyl, and cyclobutyl.

10 [0098] The terms "alkoxyl" or "alkoxy" are art-recognized and refer to an alkyl group, as defined above, having an oxygen radical attached thereto. Representative alkoxyl groups include methoxy, ethoxy, propyloxy, tert-butoxy and the like. An "ether" is two hydrocarbons covalently linked by an oxygen. Accordingly, the substituent of an alkyl that renders that alkyl an ether is or resembles an alkoxy, such as may be represented by one of -O-alkyl, -O-alkenyl, 15 or -O-alkynyl. The term "alkylene" refers to a diradical of an alkyl group. An exemplary alkylene group is -CH<sub>2</sub>CH<sub>2</sub>-.

[0099] The term "aralkyl" refers to an alkyl group substituted with an aryl group.

[00100] The term "heteroaralkyl" refers to an alkyl group substituted with a heteroaryl group.

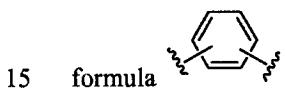
20 [00101] The term "alkenyl" refers to an unsaturated straight or branched hydrocarbon having at least one carbon-carbon double bond, such as a straight or branched group of 2-12, 2-10, or 2-6 carbon atoms, referred to herein as C<sub>2</sub>-C<sub>12</sub>alkenyl, C<sub>2</sub>-C<sub>10</sub>alkenyl, and C<sub>2</sub>-C<sub>6</sub>alkenyl, respectively. Exemplary alkenyl groups include, but are not limited to, vinyl, allyl, butenyl, pentenyl, hexenyl, butadienyl, pentadienyl, hexadienyl, 2-ethylhexenyl, 2-propyl-2-but enyl, 4-25 (2-methyl-3-butene)-pentenyl, etc.

[00102] The term "alkynyl" as used herein refers to an unsaturated straight or branched hydrocarbon having at least one carbon-carbon triple bond, such as a straight or branched group of 2-12, 2-8, or 2-6 carbon atoms, referred to herein as C<sub>2</sub>-C<sub>12</sub>alkynyl, C<sub>2</sub>-C<sub>8</sub>alkynyl, and C<sub>2</sub>-C<sub>6</sub>alkynyl, respectively. Exemplary alkynyl groups include, but are not limited to, ethynyl, 30 propynyl, butynyl, pentynyl, hexynyl, methylpropynyl, 4-methyl-1-butynyl, 4-propyl-2-pentynyl, and 4-butyl-2-hexynyl, etc.

[00103] The term "aryl" is art-recognized and refers to a carbocyclic aromatic group. Representative aryl groups include phenyl, naphthyl, anthracenyl, and the like. Unless specified otherwise, the aromatic ring may be substituted at one or more ring positions with, for example, halogen, azide, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, alkoxy, amino, 5 nitro, sulphydryl, imino, amido, carboxylic acid, -C(O)alkyl, -CO<sub>2</sub>alkyl, carbonyl, carboxyl, alkylthio, sulfonyl, sulfonamido, sulfonamide, ketone, aldehyde, ester, heterocyclyl, heteroaryl, -CF<sub>3</sub>, -CN, or the like. The term "aryl" also includes polycyclic ring systems having two or more carbocyclic rings in which two or more carbons are common to two adjoining rings (the rings are "fused rings") wherein at least one of the rings is aromatic, *e.g.*, the other cyclic rings 10 may be cycloalkyls, cycloalkenyls, cycloalkynyls, and/or aryls.

[00104] In certain embodiments, the aromatic group is not substituted, *i.e.*, it is unsubstituted.

[00105] The term "phenylene" refers to a multivalent radical (*e.g.*, a divalent or trivalent radical) of benzene. To illustrate, a divalent valent radical of benzene is illustrated by the



[00106] The terms "heterocyclyl" or "heterocyclic group" are art-recognized and refer to saturated, partially unsaturated, or aromatic 3- to 10-membered ring structures, alternatively 3- to 7-membered rings, whose ring structures include one to four heteroatoms, such as nitrogen, oxygen, and sulfur. Heterocycles may also be mono-, bi-, or other multi-cyclic ring systems. 20 A heterocycle may be fused to one or more aryl, partially unsaturated, or saturated rings. Heterocyclyl groups include, for example, biotinyl, chromenyl, dihydrofuryl, dihydroindolyl, dihydropyranyl, dihydrothienyl, dithiazolyl, homopiperidinyl, imidazolidinyl, isoquinolyl, isothiazolidinyl, isoxazolidinyl, morpholinyl, oxolanyl, oxazolidinyl, phenoxanthenyl, piperazinyl, piperidinyl, pyranyl, pyrazolidinyl, pyrazolinyl, pyridyl, pyrimidinyl, pyrrolidinyl, 25 pyrrolidin-2-onyl, pyrrolinyl, tetrahydrofuryl, tetrahydroisoquinolyl, tetrahydropyranyl, tetrahydroquinolyl, thiazolidinyl, thiolanyl, thiomorpholinyl, thiopyranyl, xanthenyl, lactones, lactams such as azetidinones and pyrrolidinones, sultams, sultones, and the like. Unless specified otherwise, the heterocyclic ring is optionally substituted at one or more positions with substituents such as alkanoyl, alkoxy, alkyl, alkenyl, alkynyl, amido, amidino, amino, aryl, 30 arylalkyl, azido, carbamate, carbonate, carboxy, cyano, cycloalkyl, ester, ether, formyl,

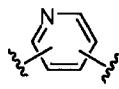
- 38 -

halogen, haloalkyl, heteroaryl, heterocyclyl, hydroxyl, imino, ketone, nitro, phosphate, phosphonato, phosphinato, sulfate, sulfide, sulfonamido, sulfonyl and thiocarbonyl. In certain embodiments, the heterocyclyl group is not substituted, *i.e.*, it is unsubstituted.

[00107] The term "heteroaryl" is art-recognized and refers to aromatic groups that include at least one ring heteroatom. In certain instances, a heteroaryl group contains 1, 2, 3, or 4 ring heteroatoms. Representative examples of heteroaryl groups include pyrrolyl, furanyl, thiophenyl, imidazolyl, oxazolyl, thiazolyl, triazolyl, pyrazolyl, pyridinyl, pyrazinyl, pyridazinyl and pyrimidinyl, and the like. Unless specified otherwise, the heteroaryl ring may be substituted at one or more ring positions with, for example, halogen, azide, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, alkoxy, amino, nitro, sulfhydryl, imino, amido, carboxylic acid, -C(O)alkyl, -CO<sub>2</sub>alkyl, carbonyl, carboxyl, alkylthio, sulfonyl, sulfonamido, sulfonamide, ketone, aldehyde, ester, heterocyclyl, aryl, -CF<sub>3</sub>, -CN, or the like. The term "heteroaryl" also includes polycyclic ring systems having two or more rings in which two or more carbons are common to two adjoining rings (the rings are "fused rings") wherein at least one of the rings is heteroaromatic, *e.g.*, the other cyclic rings may be cycloalkyls, cycloalkenyls, cycloalkynyls, and/or aryls.

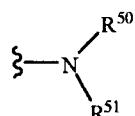
[00108] The term "heteroarylene" refers to a multi-valent (e.g., di-valent or trivalent) aromatic group that comprises at least one ring heteroatom. An exemplary "heteroarylene" is pyridinylene, which is a multi-valent radical of pyridine. For example, a divalent radical of

20 pyridine is illustrated by the formula



[00109] The terms ortho, meta and para are art-recognized and refer to 1,2-, 1,3- and 1,4-disubstituted benzenes, respectively. For example, the names 1,2-dimethylbenzene and ortho-dimethylbenzene are synonymous.

[00110] The terms "amine" and "amino" are art-recognized and refer to both unsubstituted and substituted amines, *e.g.*, a moiety that may be represented by the general formula:



wherein  $R^{50}$  and  $R^{51}$  each independently represent hydrogen, alkyl, alkenyl, or  $-(CH_2)_m-R^{61}$ ; or  $R^{50}$  and  $R^{51}$ , taken together with the N atom to which they are attached complete a heterocycle having from 4 to 8 atoms in the ring structure; wherein  $R^{61}$  is aryl, cycloalkyl, cycloalkenyl, a heterocycle or a polycycle; and m is zero or an integer in the range of 1 to 8. In certain 5 embodiments,  $R^{50}$  and  $R^{51}$  each independently represent hydrogen or alkyl.

[00111] The term "amide" or "amido" as used herein refers to a radical of the form  $-R_aC(O)N(R_b)-$ ,  $-R_aC(O)N(R_b)R_c-$ ,  $-C(O)NR_bR_c$ , or  $-C(O)NH_2$ , wherein  $R_a$ ,  $R_b$  and  $R_c$  are each independently selected from alkoxy, alkyl, alkenyl, alkynyl, amide, amino, aryl, arylalkyl, carbamate, cycloalkyl, ester, ether, formyl, halogen, haloalkyl, heteroaryl, heterocyclyl, 10 hydrogen, hydroxyl, ketone, and nitro. The amide can be attached to another group through the carbon, the nitrogen,  $R_b$ ,  $R_c$ , or  $R_a$ . The amide also may be cyclic, for example  $R_b$  and  $R_c$ ,  $R_a$  and  $R_b$ , or  $R_a$  and  $R_c$  may be joined to form a 3- to 12-membered ring, such as a 3- to 10- membered ring or a 5- to 6-membered ring. The term "carboxamido" refers to the structure  $-C(O)NR_bR_c$ .

15 [00112] The term "sulfonamide" or "sulfonamido" as used herein refers to a radical having the structure  $-N(R_r)-S(O)_2-R_s-$  or  $-S(O)_2-N(R_r)R_s$ , where  $R_r$  and  $R_s$  can be, for example, hydrogen, alkyl, aryl, cycloalkyl, and heterocyclyl. Exemplary sulfonamides include alkylsulfonamides (e.g., where  $R_s$  is alkyl), arylsulfonamides (e.g., where  $R_s$  is aryl), cycloalkyl sulfonamides (e.g., where  $R_s$  is cycloalkyl), and heterocyclyl sulfonamides (e.g., 20 where  $R_s$  is heterocyclyl), etc.

[00113] The term "sulfonyl" as used herein refers to a radical having the structure  $R_uSO_2-$ , where  $R_u$  can be alkyl, aryl, cycloalkyl, and heterocyclyl, e.g., alkylsulfonyl. The term "alkylsulfonyl" as used herein refers to an alkyl group attached to a sulfonyl group.

[00114] The symbol "~~" indicates a point of attachment.

25 [00115] Unless specified otherwise, the term "optionally substituted" as used herein means that the specified group may be substituted at one, two or more positions with, for example, halogen, azide, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, alkoxy, amino, nitro, sulphydryl, imino, amido, carboxylic acid,  $-C(O)alkyl$ ,  $-CO_2alkyl$ , carbonyl, carboxyl, alkylthio, sulfonyl, sulfonamido, sulfonamide, ketone, aldehyde, ester, heterocyclyl, heteroaryl, 30  $-CF_3$ ,  $-CN$ , or the like.

[00116] As used herein, the term “therapeutically effective amount” is understood to mean the amount of an active ingredient, for example, a necrostatin (e.g., necrostatin-1 or necrostatin-4) and/or a pan-caspase inhibitor (e.g., ZVAD or IDN-6556) that is sufficient to promote axon regeneration, preserve neuron viability, and/or promote nerve function in a CNS neuron. The 5 compounds of the invention are administered in amounts effective at, e.g., promoting axon regeneration, preserving neuron viability, promoting nerve function, increasing efficacy compared to monotherapy with either drug alone, preserving or improving cognitive functions, preserving or improving sensory functions, and/or preserving or improving motor functions. It is understood that preserving cognitive, sensory, or motor functions, includes stabilizing these 10 functions and/or slowing the decline of these functions.

[00117] As used herein, “pharmaceutically acceptable” or “pharmacologically acceptable” mean molecular entities and compositions that do not produce an adverse, allergic or other untoward reaction when administered to an animal, or to a human, as appropriate. The term, “pharmaceutically acceptable carrier” includes any and all solvents, dispersion media, coatings, 15 antibacterial and antifungal agents, isotonic and absorption delaying agents and the like. The use of such media and agents for pharmaceutical active substances is well known in the art. Except insofar as any conventional media or agent is incompatible with the active ingredient, its use in the therapeutic compositions is contemplated. Supplementary active ingredients can also be incorporated into the compositions.

20 [00118] Disclosed herein is a method for promoting axon regeneration in a CNS neuron by exposing the CNS neuron to an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote the regeneration of the axon. The CNS neuron may be *ex vivo*. For example, the CNS neuron may be isolated from a subject and maintained in an *in vitro* culture. Alternatively, the CNS neuron may be present *in vivo*.

25 [00119] Also disclosed is a method for promoting nerve function following injury to a CNS neuron. The method comprises administering to a subject an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote CNS neuron function. Further disclosed is a method for preserving the viability of a CNS neuron, wherein the method comprises administering to the subject an effective amount of a necrosis inhibitor 30 and an effective amount of an apoptosis inhibitor thereby to preserve the viability of the CNS

neuron. After administration of the necrosis inhibitor and the apoptosis inhibitor, the CNS neuron may be capable of supporting axonal regeneration.

[00120] In another aspect, the invention provides a method of treating a CNS disorder in a subject in need thereof, wherein a symptom of the CNS disorder is axon degeneration or injury within a CNS neuron. The method comprises administering to the subject an effective amount of a necrosis inhibitor and an effective amount of an apoptosis inhibitor thereby to promote regeneration of an axon in a CNS neuron affected by the CNS disorder. Following administration of the necrosis inhibitor and the apoptosis inhibitor, neuron function may be measured, for example, as an indication of axon regeneration. It is also contemplated that, following administration of the necrosis inhibitor and the apoptosis inhibitor, the neuron function of the CNS neuron is preserved or improved relative to the neuron function prior to administration of the necrosis inhibitor and the apoptosis inhibitor.

[00121] In each of the foregoing methods, the CNS disorder includes, but is not limited to, brain injury, spinal cord injury, Alzheimer's disease, amyotrophic lateral sclerosis (ALS/Lou Gehrig's Disease), Parkinson's disease, multiple sclerosis, diabetic neuropathy, polyglutamine (polyQ) diseases, stroke, Fahr disease, Menke's disease, Wilson's disease, cerebral ischemia, a prion disorder (e.g., Creutzfeldt-Jakob disease), dementia (e.g., frontotemporal dementia, dementia with Lewy bodies), corticobasal degeneration, progressive supranuclear palsy, multiple system atrophy, hereditary spastic paraparesis, and spinocerebellar atrophies.

20 [00122] In certain embodiments, the CNS disorder affects a subject's cognitive ability, such as, brain injury to the cerebral cortex or a neurodegenerative CNS disorder, such as, Alzheimer's disease, frontotemporal dementia, dementia with Lewy bodies, corticobasal degeneration, progressive supranuclear palsy, and prion disorders.

[00123] In other embodiments, the CNS disorder affects a subject's movement and/or strength, such as injury to the brain or spinal cord, or a neurodegenerative CNS disorder such as Parkinson's disease, frontotemporal dementia, dementia with Lewy bodies, corticobasal degeneration, progress supranuclear palsy, Huntington's disease, multiple system atrophy, amyotrophic lateral sclerosis, and hereditary spastic pararesis.

[00124] In yet another embodiment, the CNS disorder affects a subject's coordination, such as brain injury to the cerebellum or a neurodegenerative CNS disorder such as spinocerebellar atrophies, Friedreich's ataxia, and prion disorders.

[00125] In another aspect, the invention provides a method of promoting neuron function following injury to a CNS neuron. The method comprises reducing the production and/or activity of a RIP-1 kinase and/or RIP-3 kinase thereby promoting CNS neuron function. In certain embodiments, the reduction in the production or activity of the RIP-1 kinase and/or the RIP-3 kinase can be achieved by administering an effective amount of RIP kinase (RIPK) inhibitor, *e.g.*, a necrostatin. After treatment with the RIP kinase inhibitor, the CNS neuron may be capable of supporting axonal regeneration.

[00126] In yet another aspect, the invention provides a method of promoting axon regeneration in a CNS neuron, wherein the method comprises reducing the production and/or activity of a RIP-1 kinase and/or a RIP-3 kinase in the CNS neuron thereby promoting axon regeneration in a CNS neuron. In certain embodiments, the reduction in the production or activity of the RIP-1 kinase and/or the RIP-3 kinase can be achieved by administering an effective amount of RIP kinase (RIPK) inhibitor, *e.g.*, a necrostatin.

[00127] In each of the foregoing methods, CNS neurons include, but are not limited to, motor neurons, CNS sensory neurons, cortical neurons, cerebellar neurons, hippocampal neurons, and midbrain neurons. Exemplary motor neurons include, *e.g.*, motor neurons of the spinal cord (*e.g.*, somatic motor neurons and visceral/autonomic motor neurons), and motor neurons of the brain stem. Exemplary CNS sensory neurons include, *e.g.*, secondary sensory neurons of the spinal cord and the brain stem and sensory neurons of the cortex. Exemplary cortical neurons include pyramidal cells (*e.g.*, Betz cells), cells of Martinotti, fusiform cells, and horizontal cells of Cajal, and cortical interneurons (*e.g.*, stellate (granule) cells, Basket cells, Chandelier cells). Exemplary hippocampal neurons include pyramidal cells, hippocampal interneurons (*e.g.*, Basket cells) and granule cells. Exemplary cerebellar neurons include Purkinje cells, cerebellar interneurons (*e.g.*, Basket cells, Golgi cells) and granule cells.

[00128] Unless specified, the necrostatin can be administered to give a final concentration of greater than about 10  $\mu$ M, for example, in the range of about 10  $\mu$ M to about 1000  $\mu$ M. As described herein, the final concentration refers to final concentration in, for example, the blood, the cerebrospinal fluid, or localized region of treatment (*e.g.*, site of injury). In certain embodiments, the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount of greater than about 10  $\mu$ M. In another embodiment, the necrostatin can be administered in an amount sufficient to give a final

concentration of necrostatin in an amount of greater than about 50  $\mu$ M. In another embodiment, the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount of greater than about 100  $\mu$ M. For example, the necrostatin may be administered in an amount sufficient to give a final concentration of

5 necrostatin in an amount in the range from about 10  $\mu$ M to about 1000  $\mu$ M, 50  $\mu$ M to about 1000  $\mu$ M, 80  $\mu$ M to about 1000  $\mu$ M, about 100  $\mu$ M to about 1000  $\mu$ M, about 150  $\mu$ M to about 1000  $\mu$ M, from about 200  $\mu$ M to about 800  $\mu$ M, or from about 200  $\mu$ M to about 600  $\mu$ M. In certain embodiments, the necrostatin is administered in an amount sufficient to give a final concentration of necrostatin in an amount of about 400  $\mu$ M.

10 [00129] The apoptosis inhibitor, for example, the pan-caspase inhibitor, can be administered in an amount sufficient to give a final concentration of the inhibitor in an amount of greater than about 3  $\mu$ M, for example, in the range of about 3  $\mu$ M to about 500  $\mu$ M. In certain embodiments, the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount of greater than about 3  $\mu$ M. In another embodiment, 15 the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount of greater than about 30  $\mu$ M. In a further embodiment, the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount of greater than about 50  $\mu$ M. In yet a further embodiment, the necrostatin can be administered in an amount sufficient to give a final concentration of necrostatin in an amount 20 of greater than about 100  $\mu$ M. For example, the apoptosis inhibitor can be administered in an amount sufficient to give a final concentration of the inhibitor in an amount in the range from about 3  $\mu$ M to about 500  $\mu$ M, from about 80  $\mu$ M to about 500  $\mu$ M, 100  $\mu$ M to about 500  $\mu$ M, 125  $\mu$ M to about 500  $\mu$ M, 150  $\mu$ M to about 500  $\mu$ M or from about 200  $\mu$ M to about 400  $\mu$ M. In certain embodiments, apoptosis inhibitor (e.g., the pan-caspase inhibitor) is administered in 25 an amount sufficient to give a final concentration of the inhibitor in an amount of about 300  $\mu$ M.

[00130] In certain embodiments, from about 0.025 mg to about 4 mg, from about 0.035 mg to about 2 mg, from about 0.05 mg to about 2 mg, from about 0.1 mg to about 2 mg, from about 0.2 mg to about 1 mg, or from about 0.2 mg to about 0.8 mg of the necrosis inhibitor (e.g., a necrostatin) can be administered. In certain other embodiments, from about 0.05 mg to about 2 mg, from about 0.2 mg to about 2 mg, from about 0.05 mg to about 1.5 mg, from about 0.15

mg to about 1.5 mg, from about 0.4 mg to about 1 mg, or from about 0.5 mg to about 0.8 mg of an apoptosis inhibitor (e.g., a pan-caspase inhibitor, e.g., ZVAD) can be administered.

**[00131]** It is understood that one or more of a necrosis inhibitor, one or more of an apoptosis inhibitor, or one or more of a necrosis inhibitor and one or more of an apoptosis inhibitor can

5 be administered in amounts sufficient to preserve the viability and/or promote axon regeneration and/or nerve function of an affected CNS neuron.

**[00132]** In certain embodiments, the necrosis inhibitor is a necrostatin, for example, necrostatin-1, a necrostatin-2, a necrostatin-4, a necrostatin-5, and a necrostatin-7. One or more of these necrosis inhibitors can be administered with one or more of the apoptosis inhibitors

10 (e.g., IDN-6556) listed below. Furthermore, it is contemplated that one or more of the necrostatins shown by Formua I, I-A, I-B, I-C, I-D, I-E, I-F, I-G, II, II-A, III, IV, IV-A, IV-B, V, V-A, VII, VIII, VIII-A, IX, or IX-A can be administered with one or more of the apoptosis inhibitors (e.g., IDN-6556 or IDN-6734) listed below.

**[00133]** In certain embodiments, the necrosis inhibitor reduces the production and/or activity 15 of a RIP-1 kinase and/or a RIP-3 kinase. RIP kinase inhibitors (e.g., RIP-1 kinase and/or RIP-3 kinase inhibitors) as disclosed herein may further include RNAs, including small inhibitory RNAs (siRNAs) and short hairpin RNAs (shRNAs). Methods for designing and synthesizing siRNAs and shRNAs are well known in the art. Exemplary RIP-1 kinase inhibitors include, for example, a pSIREN-RIP-1 shRNA construct which targets RIP-1 kinase as disclosed in Kaiser

20 *et al.*, (2008) JOURNAL OF IMMUNOLOGY 181:6427-6434. Exemplary RIP-3 kinase inhibitors include, for example, sc-61482-SH and sc-135170 available from Santa Cruz Biotechnology. In another example, RIP kinase inhibitors (e.g., RIP-1 kinase and/or RIP-3 kinase inhibitors) as disclosed herein may include inhibitor of apoptosis proteins (IAPs), active fragments thereof, and nucleic acids encoding the same. It is well established that IAPs inhibit RIP-1 kinase by 25 functioning as a E3 ligase for RIP-1 kinase (see, for example, Vanlangenakker *et al.*, (2010)).

**[00134]** In certain embodiments, the one or more apoptosis inhibitors may include a pan-caspase inhibitor. The pan-caspase inhibitor can be ZVAD (*i.e.*, Z-Val-Ala-Asp(OMe)-CH<sub>2</sub>F\*), IDN-6556 available from Conatus Pharmaceuticals (*i.e.*, (3-{2-[(2-*tert*-butyl-phenylamino)oxalyl]-amino]-propionylamino}-4-oxo-5-(2,3,5,6-tetrafluoro-phenoxy)-pentanoic acid) (3-{2-[(2-*tert*-butyl-phenylamino)oxalyl]-amino]-propionylamino}-4-oxo-5-(2,3,5,6-tetrafluoro-phenoxy)-pentanoic acid), IDN-6734 available from Conatus Pharmaceuticals, VX-

799 available from Vertex Pharmaceuticals, MX1013 and MX2060 derivatives available from Maxim Pharmaceuticals, M-920 available from Merck-Frosst, small-molecule compounds available from Gemin X Pharmaceuticals, RGD peptides from Merck-Frost and Maxim Pharmaceuticals, or any other known pan-caspase inhibitor.

5 [00135] Alternatively, the pan-caspase inhibitor can be a cocktail of caspase inhibitors including two or more specific caspase inhibitors (e.g., synthetic caspase inhibitors) such as a caspase 1 inhibitor, a caspase 2 inhibitor, a caspase 3 inhibitor, a caspase 4 inhibitor, a caspase 5 inhibitor, a caspase 6 inhibitor, a caspase 7 inhibitor, a caspase 8 inhibitor, and a caspase 9 inhibitor. It is contemplated that one or more of the pan-caspase inhibitors may be used in 10 combination with one or more necrostatins (e.g., necrostatin-1 and/or necrostatin-4).

[00136] Exemplary synthetic caspase 1 inhibitors, include, for example, Ac-N-Me-Tyr-Val-Ala-Asp-aldehyde (SEQ ID NO: 7), Ac-Trp-Glu-His-Asp-aldehyde (SEQ ID NO: 8), Ac-Tyr-N-Me-Val-Ala-N-Me-Asp-aldehyde (SEQ ID NO: 9), Ac-Tyr-Val-Ala-Asp-Aldehyde (SEQ ID NO: 10), Ac-Tyr-Val-Ala-Asp-chloromethylketone (SEQ ID NO: 11), Ac-Tyr-Val-Ala-Asp-15 2,6-dimethylbenzoyloxymethylketone (SEQ ID NO: 12), Ac-Tyr-Val-Ala-Asp(OtBu)-aldehyde-dimethyl acetol (SEQ ID NO: 13), Ac-Tyr-Val-Lys-Asp-aldehyde (SEQ ID NO: 14), Ac-Tyr-Val-Lys(biotinyl)-Asp-2,6-dimethylbenzoyloxymethylketone (SEQ ID NO: 15), biotinyl-Tyr-Val-Ala-Asp-chloromethylketone (SEQ ID NO: 16), Boc-Asp(OBzl)-chloromethylketone, ethoxycarbonyl-Ala-Tyr-Val-Ala-Asp-aldehyde (pseudo acid) (SEQ ID NO: 17), Z-Asp-2,6-dichlorobenzoyloxymethylketone, Z-Asp(OtBu)-bromomethylketone, Z-Tyr-Val-Ala-Asp-chloromethylketone (SEQ ID NO: 18), Z-Tyr-Val-Ala-DL-Asp-fluoromethylketone (SEQ ID NO: 19), Z-Val-Ala-DL-Asp-fluoromethylketone, and Z-Val-Ala-DL-Asp(OMe)-fluoromethylketone, all of which can be obtained from Bachem Bioscience Inc., PA. Other exemplary caspase 1 inhibitors include, for example, Z-Val-Ala-Asp-20 fluoromethylketone, biotin-X-Val-Ala-Asp-fluoromethylketone, Ac-Val-Ala-Asp-aldehyde, Boc-Asp-fluoromethylketone, Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Leu-Ala-Leu-Leu-Pro-Tyr-Val-Ala-Asp-aldehyde (SEQ ID NO: 1), biotin-Tyr-Val-Ala-Asp-fluoroacyloxymethylketone (SEQ ID NO: 20), Ac-Tyr-Val-Ala-Asp-acyloxymethylketone (SEQ ID NO: 21), Z-Asp-CH2-DCB, and Z-Tyr-Val-Ala-Asp-fluoromethylketone (SEQ ID NO: 22), all of which are available from Calbiochem, IDN-11104 available from Conatus Pharmaceuticals, and VX-740 and VX-756 available from Vertex Pharmaceuticals.

**[00137]** Exemplary synthetic caspase 2 inhibitors, include, for example, Ac-Val-Asp-Val-Ala-Asp-aldehyde (SEQ ID NO: 23), which can be obtained from Bachem Bioscience Inc., PA, and Z-Val-Asp-Val-Ala-Asp-fluoromethylketone (SEQ ID NO: 24), which can be obtained from Calbiochem, CA.

5 **[00138]** Exemplary synthetic caspase 3 precursor protease inhibitors include, for example, Ac-Glu-Ser-Met-Asp-aldehyde (pseudo acid) (SEQ ID NO: 25) and Ac-Ile-Glu-Thr-Asp-aldehyde (pseudo acid) (SEQ ID NO: 26) which can be obtained from Bachem Bioscience Inc., PA. Exemplary synthetic caspase 3 inhibitors include, for example, Ac-Asp-Glu-Val-Asp-aldehyde (SEQ ID NO: 27), Ac-Asp-Met-Gln-Asp-aldehyde (SEQ ID NO: 28), biotinyl-Asp-10 Glu-Val-Asp-aldehyde (SEQ ID NO: 29), Z-Asp-Glu-Val-Asp-chloromethylketone (SEQ ID NO: 30), Z-Asp(OMe)-Glu(OMe)-Val-DL-Asp(OMe)-fluoromethylketone (SEQ ID NO: 31), and Z-Val-Ala-DL-Asp(OMe)-fluoromethylketone which can be obtained from Bachem Bioscience Inc., PA. Other exemplary caspase 3 inhibitors include, for example, Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Ala-Leu-Ala-Pro-Asp-Glu-Val-Asp-aldehyde 15 (SEQ ID NO: 2), biotin-X-Asp-Glu-Val-Asp-fluoromethylketone (SEQ ID NO: 32), Ac-Asp-Glu-Val-Asp-chloromethylketone (SEQ ID NO: 33), all of which are available from Calbiochem. Another exemplary caspase 3 inhibitor includes, the caspase 3 inhibitor *N*-benzyloxycarbonal-Asp(OMe)-Glu(OMe)-Val-Asp(Ome)-fluoromethylketone (z-Asp-Glu-Val-Asp-fmk) (SEQ ID NO: 34), which is available from Enzyme Systems Products. Additional 20 exemplary caspase 3 inhibitors include M-826 and M-791 available from Merck-Frosst, Immunocasp-3, Ad-G/iCasp3, and PEF-F8-CP3.

**[00139]** Exemplary synthetic caspase 4 inhibitors include, for example, Ac-Leu-Glu-Val-Asp-aldehyde (SEQ ID NO: 35) and Z-Tyr-Val-Ala-DL-Asp-fluoromethylketone (SEQ ID NO: 36), which can be obtained from Bachem Bioscience Inc., PA, and Ac-Ala-Ala-Val-Ala-Leu-25 Pro-Ala-Val-Leu-Ala-Leu-Ala-Pro-Leu-Glu-Val-Pro-aldehyde (SEQ ID NO: 3), which can be obtained from Calbiochem, CA.

**[00140]** Exemplary synthetic caspase 5 inhibitors include, for example, Z-Trp-His-Glu-Asp-fluoromethylketone (SEQ ID NO: 37), which can be obtained from Calbiochem, CA, and Ac-Trp-Glu-His-Asp-aldehyde (SEQ ID NO: 38) and Z-Trp-Glu(O-Me)-His-Asp(O-Me) 30 fluoromethylketone (SEQ ID NO: 39), which can be obtained from Sigma Aldrich, Germany.

[00141] Exemplary synthetic caspase 6 inhibitors include, for example, Ac-Val-Glu-Ile-Asp-aldehyde (SEQ ID NO: 40), Z-Val-Glu-Ile-Asp-fluoromethylketone (SEQ ID NO: 41), and Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Leu-Ala-Pro-Val-Glu-Ile-Asp-aldehyde (SEQ ID NO: 4), which can be obtained from Calbiochem. Another exemplary caspase 6 inhibitor includes Immunocasp-6.

[00142] Exemplary synthetic caspase 7 inhibitors include, for example, Z-Asp(OMe)-Gln-Met-Asp(OMe) fluoromethylketone (SEQ ID NO: 42), Ac-Asp-Glu-Val-Asp-aldehyde (SEQ ID NO: 43), Biotin-Asp-Glu-Val-Asp-fluoromethylketone (SEQ ID NO: 44), Z-Asp-Glu-Val-Asp-fluoromethylketone (SEQ ID NO: 45), Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Leu-Ala-Leu-Ala-Pro-Asp-Glu-Val-Asp-aldehyde (SEQ ID NO: 2), which can be obtained from Sigma Aldrich, Germany.

[00143] Exemplary synthetic caspase 8 inhibitors include, for example, Ac-Asp-Glu-Val-Asp-aldehyde (SEQ ID NO: 46), Ac-Ile-Glu-Pro-Asp-aldehyde (SEQ ID NO: 47), Ac-Ile-Glu-Thr-Asp-aldehyde (SEQ ID NO: 48), Ac-Trp-Glu-His-Asp-aldehyde (SEQ ID NO: 49) and Boc-Ala-Glu-Val-Asp-aldehyde (SEQ ID NO: 50) which can be obtained from Bachem Bioscience Inc., PA. Other exemplary caspase 8 inhibitors include, for example, Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Ala-Leu-Ala-Pro-Ile-Glu-Thr-Asp-aldehyde (SEQ ID NO: 5) and Z-Ile-Glu-Thr-Asp-fluoromethylketone (SEQ ID NO: 51), which can be obtained from Calbiochem, CA.

[00144] Exemplary synthetic caspase 9 inhibitors, include, for example, Ac-Asp-Glu-Val-Asp-aldehyde (SEQ ID NO: 52), Ac-Leu-Glu-His-Asp-aldehyde (SEQ ID NO: 53), and Ac-Leu-Glu-His-Asp-chloromethylketone (SEQ ID NO: 54) which can be obtained from Bachem Bioscience Inc., PA. Other exemplary caspase 9 inhibitors include, for example, Z-Leu-Glu-His-Asp-fluoromethylketone (SEQ ID NO: 55) and Ac-Ala-Ala-Val-Ala-Leu-Leu-Pro-Ala-Val-Leu-Ala-Leu-Ala-Pro-Leu-Glu-His-Asp-aldehyde (SEQ ID NO: 6), which can be obtained from Calbiochem, CA. Another exemplary caspase 9 inhibitor includes FKBP12/caspase-9 fusion protein.

[00145] The pan-caspase inhibitor may also be an endogenous caspase inhibitor or a combination of an endogenous caspase inhibitor with one or more synthetic caspase inhibitors. For example, one useful class of endogenous caspase inhibitor includes proteins known as inhibitors of apoptosis proteins (IAPs) (Deveraux *et al.*, (1998) EMBO J. 17(8): 2215-2223)

including bioactive fragments and analogs thereof. One exemplary IAP includes X-linked inhibitor of apoptosis protein (XIAP), which has been shown to be a direct and selective inhibitor of caspase-3, caspase-7 and caspase-9. Another exemplary IAP includes survivin (see, U.S. Patent No. 6,245,523; Papapetropoulos *et al.*, (2000) J. BIOL. CHEM. 275: 9102-9105), including bioactive fragments and analogs thereof. Survivin has been reported to inhibit caspase-3 and caspase-7 activity.

**[00146]** In certain embodiments, the one or more apoptosis inhibitors may target the inhibitor of apoptosis proteins (IAPs) and second mitochondria-derived activator of caspases (SMACs). Exemplary apoptosis inhibitors that target IAPs and SMACs, include, for example, 10 BIR3 antagonists available from Idun Pharmaceuticals, capped tripeptide XIAP antagonists from Abbot Laboratories, TWX024, polyphenylurea derivatives, SMAC-mimetic compounds, embelin, XIAP antisense and RNAi constructs, AEG35156/GEM®640 available from Aegera Therapeutics, HIV-Tat- and polyarginine conjugated SMAC peptides, and nonpeptide small-molecule SMAC mimetics. It is contemplated that one or more of the apoptosis inhibitors 15 which target IAPs and SMACs may be used in combination with one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4).

**[00147]** In certain embodiments, the one or more apoptosis inhibitors may target the TNF-related apoptosis-inducing ligand (TRAIL) receptors. Exemplary apoptosis inhibitors that target the TRAIL receptors, include, for example, HGS-ETR1, HGS-ETR2, and HGS-TR2J 20 available from Human Genome Sciences, and PRO1762 available from Amgen. It is contemplated that one or more of the apoptosis inhibitors which target the TRAIL receptors may be used in combination with one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4).

**[00148]** In certain embodiments, the one or more apoptosis inhibitors may target CD95/Fas. 25 Exemplary apoptosis inhibitors that target CD95/FAS, include, for example, CD95-Fc available from ApoGenix GmbH. It is contemplated that one or more of the apoptosis inhibitors which target CD95/Fas may be used in combination with one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4).

**[00149]** In certain embodiments, the one or more apoptosis inhibitors may be an anti-FasL 30 factors. Exemplary anti-FasL factors include, for example, anti-FasL neutralizing antibody (available, for example, from Pharmingen, San Diego, CA); peptides and nucleic acids (for

example, anti-FasL aptamers) that bind FasL to prevent or reduce its binding to its cognate receptor; certain antibodies and antigen binding fragments thereof and peptides that bind preferentially to the Fas receptor; antisense nucleotides and double stranded RNA for RNAi that ultimately reduce or eliminate the production of either FasL or the Fas receptor; soluble

5 Fas; soluble FasL; decoy receptor-3 (DcR3) and analogues thereof; matrix metalloproteinases (MMPs); vasoactive intestinal peptide (VIP); pituitary adenylate cyclase-activating polypeptide (PACAP); forskolin; combined use of benazepril and valsartan; nonpeptidic corticotropin-releasing hormone receptor type 1 (CRH-R1)-specific antagonists; mimosine; peptides that produce a defective Fas-FasL complex; platelet-activating factor (PAF); and endothelin-1 (ET-10). These anti-FasL factors can act as direct or indirect antagonists of FasL activity.

[00150] In certain embodiments, the one or more apoptosis inhibitors may target the tumor necrosis factor (TNF). Exemplary apoptosis inhibitors that target TNF, include, for example, recombinant TNF- $\alpha$ , adalimumab available from Abbott, infliximab available from Centocor Ortho Biotech Inc., etanercept from Amgen, CDP571 available from Celltech, and ISIS 104838

15 (a 2'-O-methoxyethyl antisense construct against TNF-alpha) available from ISIS Pharmaceuticals. It is contemplated that one or more of the apoptosis inhibitors which target TNF may be used in combination with one or more necrostatins (e.g., necrostatin-1 and/or necrostatin-4).

[00151] In certain embodiments, the one or more apoptosis inhibitors may target survivin.

20 Exemplary apoptosis inhibitors that target survivin, include, for example, LY2181308 available from ISIS Pharmaceuticals and Ad-survivin T34A. It is contemplated that one or more of the apoptosis inhibitors which target survivin may be used in combination with one or more necrostatins (e.g., necrostatin-1 and/or necrostatin-4).

[00152] In certain embodiments, the one or more apoptosis inhibitors may target the Bcl-2

25 proteins. Exemplary apoptosis inhibitors that target the Bcl-2 proteins, include, for example, Bcl-2 blockers available from Idun Pharmaceuticals and Abbot Laboratories, Gx01 series of compounds available from Gemin X Pharmaceuticals, Bcl-2 small-molecule antagonist, Tetrocacin-A derivatives available from Kyowa Hakko Kogyo Co., Chelerythrine, antimycin A derivatives, HA14-1, synthetic compound binding to the BH3 of Bcl-2, Genasense available 30 from Sanofi-Aventis, ISIS 22783 available from ISIS Pharmaceuticals, bispecific Bcl-2/Bcl-XL antisense, BH3 peptides from Bax, Bak, Bid or Bad, SAHBs, and BH3Is. It is contemplated

that one or more of the apoptosis inhibitors which target the Bcl-2 proteins may be used in combination with one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4).

[00153] In certain embodiments, the one or more apoptosis inhibitors may target p53. Exemplary apoptosis inhibitors that target p53, include, for example, INGN201 available from 5 Invitrogen Therapeutics, SCH58500 available from Schering-Plough, ONYX-015 available from Onyx Pharmaceuticals, C-terminal p53 peptides, CDB3, Amifostine, CP31398 available from Pfizer, Prima-1, HPF E6-binding peptide aptamers, Nutlins available from Roche, Chalcones, Small peptide compounds, and Pifithrin- $\alpha$ . It is contemplated that one or more of the apoptosis inhibitors which target p53 may be used in combination with one or more 10 necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4).

[00154] In certain embodiments, it is contemplated that one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4) may be used in combination with a pan-caspase inhibitor. For example, in one embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with ZVAD available from R&D Systems (Cat. No. FMK001) and Promega (Cat. 15 No. G7231). In another embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with IDN-6556 available from Conatus Pharmaceuticals. In yet another embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with IDN-6734 available from Conatus Pharmaceuticals.

[00155] In certain embodiments, it is contemplated that one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4) may be used in combination with a TNF inhibitor. For example, in one embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with adalimumab available from Abbot Laboratories. In another embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with etanercept available from Amgen, Inc. In yet another embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with 25 infliximab available from Centocor Ortho Biotech, Inc.

[00156] In certain embodiments, it is contemplated that one or more necrostatins (*e.g.*, necrostatin-1 and/or necrostatin-4) may be used in combination with a p53 agonist. For example, in one embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with INGN 201 available from Invitrogen Therapeutics. In another embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with nutlins, for example, nutlin-3 available 30 from Cayman Chemical (Cat. No. 10004372). In another embodiment, necrostatin-1 and/or

necrostatin-4 may be used in combination with CP31398 available from Tocris Bioscience (Cat. No. 3023).

[00157] In certain embodiments, it is contemplated that one or more necrostatins (e.g., necrostatin-1 and/or necrostatin-4) may be used in combination with an anti-FasL factor. For 5 example, in one embodiment, necrostatin-1 and/or necrostatin-4 may be used in combination with anti-FasL neutralizing antibody available from Pharmingen (San Diego, CA).

[00158] Without wishing to be bound by theory, but as shown in Figure 1, depending upon the specific apoptotic inhibitor chosen, it is possible that the apoptotic inhibitor can modulate both the apoptotic and necrotic pathways, and depending upon the specific necrosis inhibitor 10 chosen, it is possible that the necrosis inhibitor can modulate both the necrotic and apoptotic pathways. For example, a RIP-1 inhibitor may inhibit both necrotic and apoptotic cell death thus preserving the viability of CNS neurons and promoting axon regeneration in a subject with a CNS disorder as disclosed herein.

[00159] As discussed herein, the disclosed methods promote axon regeneration of a CNS 15 neuron. Further, the disclosed methods preserve neuron viability and/or promote nerve function following injury to a CNS neuron. Assessment of axonal regeneration and nerve function may be monitored by, functional tests which are well-established in the art, such as, for example, magnetic resonance imaging (MRI) and tests involving evaluations of a subject's cognitive, motor, and sensory functions.

20 [00160] For example, axon regeneration in a patient suffering from spinal cord injury may be measured by improvements according to the Frankel classification system, the American Spinal Injury Association (ASIA) classification system, the Yale classification system, the motor index scale, the modified Barthel index, the Basso, Beattie and Bresnahan (BBB) scale, and the like. Recovery from neuron injury can also be monitored by a neurological 25 examination which assesses motor and sensory skills, the functioning of one or more cranial nerves, hearing and speech, vision, coordination and balance, mental status, and changes in mood or behavior, among other abilities. For example, items such as a tuning fork, flashlight, reflex hammer, ophthalmoscope, and needles may be used to evaluate motor and sensory functions. In another example, evoked potential (also called evoked response) may be 30 employed to measure the electrical signals to the brain generated by hearing, touch, or sight, which serve as an assessment of sensory function. In a further example, neurological computed

tomography, also known as a neurological CT scan, may be performed to monitor recovery from brain damage.

[00161] In another example, axonal regeneration in a stroke patient may be measured by the NIH Stroke Scale (NIHSS). The NIHSS is a standardized neurological examination that

5 measures several aspects of brain function, including consciousness, vision, sensation, movement, speech, and language, and is intended describe the neurological deficits found in stroke patients. Other functional tests may be based on, for example, the Barthel Index (BI), which measures self-care and mobility. The BI assesses a subject's ability to perform tasks such as personal toileting, feeding, mobility from bed to chair, transfers, and bathing.

10 Functional test may also include the Modified Rankin Scale (mRS), which is commonly used for measuring the degree of disability or dependence in the daily activities of stroke patients.

[00162] Any appropriate route of administration may be employed. For example, the necrosis inhibitor and the apoptosis inhibitor may be administered directly to the site of injury or systemically, *e.g.*, by oral or parenteral routes. Parenteral routes include, for example,

15 intravenous, intrarterial, intracranial, intraorbital, ophthalmalic, intraventricular, intraspinal (*e.g.*, into the cerebrospinal fluid), intracisternal, intramuscular, intradermal, subcutaneous, intranasal and intraperitoneal routes. It is contemplated that local modes of administration may reduce or eliminate the incidence of potential side effects (*e.g.*, systemic toxicity) that may occur during systemic administration.

20 [00163] The necrosis inhibitor and the apoptosis inhibitor may be administered to a subject simultaneously or sequentially. It will be appreciated that when administered simultaneously, the necrosis inhibitor and the apoptosis inhibitor may be in the same pharmaceutically acceptable carrier or the two drugs may be dissolved or dispersed in separate pharmaceutical carriers, which are administered at the same time. Alternatively, the drugs may be provided in

25 separate dosage forms and administered sequentially. For example, in some embodiments, the necrostatin may be administered before the pan-caspase inhibitor. In other examples, the pan-caspase inhibitor may be administered before the necrostatin. In addition, it is appreciated that, in some embodiments, a single active agent may inhibit both necrosis and apoptosis.

[00164] Administration may be provided as a periodic bolus (for example, intravenously) or

30 as continuous infusion from an internal reservoir or from an external reservoir (for example, from an intravenous bag). The necrosis inhibitor and/or the apoptosis inhibitor may be

administered locally, for example, by continuous release from a sustained release drug delivery device.

[00165] The necrosis inhibitor and/or the apoptosis inhibitor may be solubilized in a pharmaceutically acceptable carrier. One or both inhibitors also may be administered in a pharmaceutically acceptable carrier or vehicle so that administration does not otherwise adversely affect the recipient's electrolyte and/or volume balance. The carrier may comprise, for example, physiologic saline or other buffer system. In exemplary embodiments, the necrostatin, the pan-caspase inhibitor, or both the necrostatin and the pan-caspase inhibitor may be solubilized in PBS or another aqueous buffer by sonication. Alternatively, one or both drugs may be solubilized using conventional solvent or solubilization systems, for example, dimethyl sulfoxide (DMSO), dimethoxyethane (DME), dimethylformamide (DMF), cyclodextran, micelles, liposomes, liposomal agents, and other solvents known in the art to aid in the solubilization and administration of hydrophobic agents.

[00166] In other embodiments, the necrosis inhibitor and/or the apoptosis inhibitor may be solubilized in a liposome or microsphere. Methods for delivery of a drug or combination of drugs in liposomes and/or microspheres are well-known in the art.

[00167] In addition, it is contemplated that the necrosis inhibitor and/or the apoptosis inhibitor may be formulated so as to permit release of one or both inhibitors over a prolonged period of time. A release system can include a matrix of a biodegradable material or a material, which releases the incorporated active agents. The active agents can be homogeneously or heterogeneously distributed within a release system. A variety of release systems may be useful in the practice of the invention, however, the choice of the appropriate system will depend upon the rate of release required by a particular drug regime. Both non-degradable and degradable release systems can be used. Suitable release systems include polymers and polymeric matrices, non-polymeric matrices, or inorganic and organic excipients and diluents such as, but not limited to, calcium carbonate and sugar (for example, trehalose). Release systems may be natural or synthetic. However, under certain circumstances, synthetic release systems are preferred because generally they are more reliable, more reproducible and produce more defined release profiles. The release system material can be selected so that inhibitors having different molecular weights are released by diffusion through or degradation of the material.

- 54 -

**[00168]** Representative synthetic, biodegradable polymers include, for example: polyamides such as poly(amino acids) and poly(peptides); polyesters such as poly(lactic acid), poly(glycolic acid), poly(lactic-co-glycolic acid), and poly(caprolactone); poly(anhydrides); polyorthoesters; polycarbonates; and chemical derivatives thereof (substitutions, additions of 5 chemical groups, for example, alkyl, alkylene, hydroxylations, oxidations, and other modifications routinely made by those skilled in the art), copolymers and mixtures thereof. Representative synthetic, non-degradable polymers include, for example: polyethers such as poly(ethylene oxide), poly(ethylene glycol), and poly(tetramethylene oxide); vinyl polymers- polyacrylates and polymethacrylates such as methyl, ethyl, other alkyl, hydroxyethyl 10 methacrylate, acrylic and methacrylic acids, and others such as poly(vinyl alcohol), poly(vinyl pyrrolidone), and poly(vinyl acetate); poly(urethanes); cellulose and its derivatives such as alkyl, hydroxyalkyl, ethers, esters, nitrocellulose, and various cellulose acetates; polysiloxanes; and any chemical derivatives thereof (substitutions, additions of chemical groups, for example, alkyl, alkylene, hydroxylations, oxidations, and other modifications routinely made by those 15 skilled in the art), copolymers and mixtures thereof.

**[00169]** Treatment can be continued for as long or as short a period as desired. For example, treatments may be administered on a regimen of, for example, one to four or more times per day, one to four or more times per week, one to four or more times per month. A suitable treatment period may be, for example, at least one day, at least about one week, at least about 20 two weeks, at least about one month, at least about six months, at least about 1 year, or indefinitely.

**[00170]** Throughout the description, where compositions are described as having, including, or comprising specific components, or where processes are described as having, including, or comprising specific process steps, it is contemplated that compositions of the present invention 25 also consist essentially of, or consist of, the recited components, and that the processes of the present invention also consist essentially of, or consist of, the recited processing steps. Further, it should be understood that the order of steps or order for performing certain actions are immaterial so long as the invention remains operable. Moreover, two or more steps or actions may be conducted simultaneously.

- 55 -

## EXAMPLES

[00171] The invention is further illustrated by the following examples, which are provided for illustrative purposes only, and should not be construed as limiting the scope or content of the invention in any way.

5 [00172] In the examples described herein, all animal experiments adhered to the Association for Research in Vision and Ophthalmology Statement for the Use of Animals in Ophthalmic and Vision Research, and protocols were approved by the Animal Care Committee of the Massachusetts Eye and Ear Infirmary. Wild-type C57BL/6 mice were purchased from Charles River Laboratories (Wilmington, MA). The mice were fed standard laboratory chow and  
10 allowed free access to water in an air-conditioned room with a 12 hour light/12 hour dark cycle. Except as noted otherwise, the animals were anesthetized with ketamine hydrochloride (30 mg/kg; Ketalar, Parke-Davis, Morris Plains, NJ) and xylazine hydrochloride (5 mg/kg; Rompun, Harver-Lockhart, Morris Plains, NJ) before all experimental manipulations.

15 [00173] The following reagents were utilized: ZVAD (Alexis, Plymouth Meeting PA), IDN-6556 (kindly provided by TetraLogics Pharmaceuticals), and a Nec-1 compound of Formula I-C (a kind gift from Dr. J. Yuan, Harvard Medical School, Boston, MA).

20 [00174] Intravitreal injections were performed as follows. Briefly, the tip of a 33 gauge needle (Hamilton, Reno, NV) was carefully inserted through the sclera into the intravitreal space to reduce intraocular pressure. Then, the needle was extracted, loaded with compounds and tangentially reinserted through the sclera into the intravitreal space, inducing a self-sealing wound tunnel. After injection, the absence of choroidal bleeding was confirmed. At specified times after injury, mice were sacrificed with an overdose of sodium pentobarbital, and eyes  
25 were enucleated.

25 [00175] TUNEL and quantification of TUNEL (+) cells were performed as previously described (Nakazawa *et al.*, 2007) by using the ApopTag Fluorescein *In Situ* Apoptosis Detection Kit (S7110; Chemicon International, Temecula, CA).

30 [00176] All values disclosed were expressed as the mean  $\pm$  SD. Statistical differences between two groups were analyzed by Mann-Whitney *U* test. Multiple group comparison was performed by ANOVA followed by Tukey-Kramer adjustments. Differences were considered significant at  $P < 0.05$ .

**Example 1: Efficacy of a Necrosis Inhibitor and a Pan-Caspase Inhibitor in Promoting RGC Survival and Axon Regeneration**

[00177] Like most pathways in the mature central nervous system, the optic nerve cannot regenerate if injured, leaving victims of traumatic nerve injury or degenerative diseases such as 5 glaucoma with life-long visual losses. This situation can be, at least, partially reversed by enhancing the intrinsic growth state of retinal ganglion cells (RGCs). In this example, the efficacy of necrosis inhibitor and a pan-caspase inhibitor in promoting RGC survival and axon regeneration is investigated using a mouse optic nerve crush model.

10 **A. A Necrosis Inhibitor in Combination with a Caspase Inhibitor Promotes RGC Survival in a Optic Nerve Crush Model**

[00178] Mice were subjected to optic nerve crush surgery. Specifically, animals were anesthetized with an intraperitoneal injection of ketamine (60–80 mg/kg; Phoenix 15 Pharmaceutical, St. Joseph, MO) and xylazine (10–15 mg/kg; Bayer, Shawnee Mission, KA). Animals were positioned in a stereotaxic apparatus and a 1–1.5 cm incision was made in the 20 skin above the right orbit. Under microscopic illumination, the lachrymal glands and extraocular muscles were resected to expose 3–4 mm of the optic nerve. The epineurium was slit open along the long axis, and the nerve was crushed 2 mm behind the eye with angled jeweler's forceps (Dumont # 5) for 10 seconds, avoiding injury to the ophthalmic artery. Nerve injury was verified by the appearance of a clearing at the crush site, while the vascular integrity 25 of the retina was evaluated by fundoscopic examination. Cases in which the vascular integrity of the retina was in question were excluded from the study.

[00179] Following surgery, mice were divided into four groups for treatment: vehicle group, ZVAD group (300  $\mu$ M; given at day 0, day 3 and day 7 after injury), Nec-1 group (4 mM; given at day 0, day 3 and day 7 after injury), and ZVAD plus Nec-1 group (300  $\mu$ M and 4 mM, 25 respectively; given either once or at day 0, day 3 and day 7 after injury). Soon after injury, each group received an intravitreal injection (3  $\mu$ l) with the respective compounds. As a control, one group of mice were injected with Zymosan (12.5  $\mu$ g/ $\mu$ l), a yeast cell wall preparation, known to stimulate axonal regeneration.

[00180] Fourteen days following injection, the number of RGCs were measured by staining 30 with an anti-Brn3a antibody. Specifically, eyes were enucleated and RGC loss was quantified

from histological sections of mouse retina. Images of eight prespecified areas, 2mm from the optic disc, were captured under fluorescent illumination (2 points/section x 4 sections per eye, n = 8) using a camera (Nikon E800). Brn3a-positive cells were counted using NIH ImageJ software.

5 [00181] As seen in Figure 2, a combination of ZVAD and Nec-1 significantly prevented RGC death and promoted RGC survival following optic nerve crush injury when compared to treatment with Zymosan alone (p<0.05). The effect of the ZVAD and Nec-1 combination treatment on RGC survival was even more pronounced when the treatment was given at day 0, day 3 and day 7 after injury when compared to a single treatment at day 0 (p<0.05).

10 **B. A Necrosis Inhibitor in Combination with a Caspase Inhibitor Promotes Axon Regeneration**

[00182] To investigate the efficacy of necrosis inhibitor and pan-caspase inhibitor in promoting axon regeneration, eight-weeks-old mice were subjected to optic nerve crush surgery as previously described. Subsequently, injured mice were divided into five groups of 15 treatment: vehicle group, ZVAD group (300  $\mu$ M; given at day 0, day 3 and day 7 after injury), Nec-1 group (4 mM; given at day 0, day 3 and day 7 after injury), ZVAD plus Nec-1 group (300  $\mu$ M and 4 mM, respectively; given once at day 0), and ZVAD plus Nec-1 group (300  $\mu$ M and 4 mM, respectively; given at day 0, day 3 and day 7 after injury).

[00183] Axon regeneration was assessed by obtaining longitudinal sections of the optic nerve and counting the number of axons at pre-specified distances from the injury site. Specifically, mice were sacrificed at 14 days after optic nerve injury and were perfused with saline and 4% paraformaldehyde (PFA). Optic nerves and eyes were dissected and postfixed in PFA. Nerves were impregnated with 10% and then 30% sucrose, embedded in OCT Tissue Tek Medium (Sakura Finetek), frozen, cut in the longitudinal plane at 14  $\mu$ m, and mounted on 25 coated slides. Regenerating axons were visualized by staining with a sheep antibody to  $\beta$ III-tubulin, followed by staining with a fluorescently labeled secondary antibody. Axons were counted manually in at least eight longitudinal sections per case at pre-specified distances from the injury site. The number of regenerating axons at various distances are determined as described previously (Leon et al., (2000) J NEUROSCI 20:4615–4626). To determine the 30 number of surviving cells, staining with an anti-Brn3a antibody was used.

[00184] Figures 3A-3E show longitudinal sections of the optic nerve following optic nerve crush injury. The sections are stained with an antibody against  $\beta$ III-tubulin, which marks axon fibers. In each photograph, an arrow indicates the sites of optic nerve injury, and staining beyond the injury site starting from left to right indicates axon regeneration (e.g., axons regenerate from the site of injury into the nerve). No significant axon regeneration was seen in mice treated with vehicle control, as demonstrated by the lack of axon staining (Figure 3A). Treatment with Nec-1 or ZVAD alone had minimal effects on axon regeneration (Figures 3B and 3C). In contrast, ZVAD plus Nec-1 combination treatment significantly enhanced axon outgrowth as demonstrated by the increase in axon staining (Figures 3D and 3E; see the regions 5 denoted by the horizontal reference lines under each figure). Further, as shown in Figures 3D and 3E, the effect of the ZVAD and Nec-1 combination treatment on axon regeneration was more pronounced when the treatment was given at day 0, day 3 and day 7 after injury when compared to a single treatment at day 0. These results indicate that ZVAD and Nec-1 combination treatment not only ameliorates the loss of RGC following optic nerve injury but 10 also promotes axon regeneration following injury.

15

**Example 2: Efficacy of a Necrosis Inhibitor and a Pan-Caspase Inhibitor in a Rat Model of Motor Neuron Regeneration**

[00185] The specificity of motor axon regeneration can be investigated in the rat femoral nerve. Proximally, at the site of nerve transection and suture, axons that contribute to both 20 cutaneous and muscle branches intermingle throughout the nerve. As these axons regenerate, they have equal access to neighboring motor and sensory Schwann cell tubes in the distal nerve stump. This assures an element of "choice" at the axonal level. Distally, where the specificity of regeneration is assessed, axons are segregated into terminal cutaneous and muscle branches. Motor axons are normally found only in the muscle branch, so any motor reinnervation of the 25 cutaneous branch represents a pathfinding failure. The specificity of axon regeneration is evaluated by simultaneous application of horseradish peroxidase (HRP) to one distal femoral branch and fluoro-gold (FG) to the other. Motor-axon regeneration is random at 3 weeks, but the number of correct projections to muscle increases dramatically at later times. Many neurons initially contain both tracers, and thus project collaterals to both cutaneous and muscle 30 branches. The number of these double-labeled neurons decreases with time. Motor axon collaterals are thus pruned from the cutaneous branch, increasing the number of correct

projections to muscle at the expense of double-labeled neurons. A specific interaction thus occurs between regenerating motor axons and muscle and/or muscle nerve.

[00186] To assess the efficacy of a necrosis inhibitor and a pan-caspase inhibitor in modifying motor axon regeneration, rats are divided into four treatment groups: vehicle group, 5 ZVAD group, Nec-1 group, and ZVAD plus Nec-1 group. These agents are pumped onto the repair site, using an Alzet osmotic pump for at least 2 weeks. The outlet of the pump is sewn to muscle adjacent to the nerve repair, so that the nerve wound is continuously bathed with the necrosis inhibitor and the apoptosis inhibitor. Reinnervation of the distal femoral cutaneous and muscle branches can be quantified with tracers as described above.

10 [00187] After three weeks, motor regeneration is evaluated by assessing the number of motoneurons that projected correctly to muscle and those that projected incorrectly to the skin. It is contemplated that mice treated with ZVAD plus Nec-1 will show an increase in the mean number of correct projections and a reduction in the mean number of incorrect projections to skin relative to controls.

15 **Example 3: Efficacy of a Necrosis Inhibitor and a Pan-Caspase Inhibitor in a Rat Model of Damaged Vertebra**

[00188] Two-month old Sprague-Dawley rats (200-220 g) are used. Starting from 14 days before surgical operations, the animals undergo basic walking training for the Basso, Beattie and Bresnahan (BBB) test and the grid walk test, which measure locomotor functions. At 3 20 days before surgical operations, the animals are subjected to basic evaluations with respect to their behaviors and movement functions.

[00189] Rats are anesthetized with 2 kg/ml of a mixture of 25 mg/ml of ketamine and 1.3 mg/ml of Rompun and subjected to L2 Ventral Laminectomy. The animals are intramuscularly injected with the antibiotic Cefalexin (5 mg/100 g bodyweight/day) to prevent infections.

25 Spinal cord injury is induced by opening the second lumbar vertebra of each rat and puncturing a small hole (1 mm<sup>2</sup>) in the outside of the left arcus vertebra using a microrongeur. The blade of a blade holder is inserted into the hole and knifed via the dura mater to the outside of the right arcus vertebra, thus causing traumatic damage at the abdominal portion of the spine. The dorsal musculature of the damaged spinal nerve portion is sutured and ligated with surgical 30 clips. After the surgical operation, the rats are placed on warm sawdust to maintain their body temperature, and the portion below the abdominal region is massaged 3-4 times every day for 7

- 60 -

days so as to discharge the content of the bladder, until the autonomic bladder control thereof is completely restored.

[00190] Following injury, the rats are divided into four treatment groups: vehicle group, ZVAD group (given at day 0, day 3 and day 7 after injury), Nec-1 group (given at day 0, day 3 and day 7 after injury), and ZVAD plus Nec-1 group (given at day 0, day 3 and day 7 after injury).

[00191] At thirty days post surgery, the rats are subjected to functional tests, such as the BBB test or the grid walk test, which measure their open-field walking ability and motor functions. The rats are further subjected to tests such as the footprint analysis, 10 electrophysiological analysis, and histological analysis, which are known in the art, to further assess their recovery of locomotor functions. It is contemplated that rats which are treated with ZVAD plus Nec-1 will show greater improvements in locomotor functions when compared to rats treated with vehicle or with ZVAD or Nec-1 only.

#### INCORPORATION BY REFERENCE

[00192] The entire disclosure of each of the patent documents and scientific articles cited 15 herein are incorporated by reference in their entirety for all purposes.

#### EQUIVALENTS

[00193] The invention can be embodied in other specific forms with departing from the essential characteristics thereof. The foregoing embodiments therefore are to be considered 20 illustrative rather than limiting on the invention described herein. The scope of the invention is indicated by the appended claims rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are intended to be embraced therein.

[00194] What is claimed is :

- 1 1. A method for promoting axon regeneration in a CNS neuron, the method comprising:
  - 2 exposing the CNS neuron to an effective amount of a necrosis inhibitor and an effective
  - 3 amount of an apoptosis inhibitor thereby to promote the regeneration of the axon.
- 1 2. The method of claim 1, wherein the neuron is *ex vivo*.
- 1 3. The method of claim 1, wherein the neuron is *in vivo*.
- 1 4. A method of promoting neuron function following injury to a central nervous system (CNS)  
2 neuron, the method comprising:
  - 3 administering to a subject in need thereof an effective amount of a necrosis inhibitor
  - 4 and an effective amount of an apoptosis inhibitor thereby to promote CNS neuron function.
- 1 5. A method of preserving the viability of a CNS neuron, the method comprising:
  - 2 administering to a subject in need thereof an effective amount of a necrosis inhibitor
  - 3 and an effective amount of an apoptosis inhibitor thereby to preserve the viability of the CNS
  - 4 neuron.
- 1 6. The method of claim 4 or 5, wherein after treatment with the necrosis inhibitor and the  
2 apoptosis inhibitor, the CNS neuron is capable of supporting axonal regeneration.
- 1 7. A method of treating a CNS disorder in a subject in need thereof, wherein a symptom of the  
2 CNS disorder is axon degeneration within a CNS neuron, the method comprising:
  - 3 administering to the subject an effective amount of a necrosis inhibitor and an effective
  - 4 amount of an apoptosis inhibitor thereby to promote regeneration of an axon in a CNS neuron
  - 5 affected by the CNS disorder.
- 1 8. The method of claim 5 or 7, further comprising, after the administration of a necrosis  
2 inhibitor and an apoptosis inhibitor, measuring neuron function within the subject.
- 1 9. The method of claim 8, wherein the neuron function is an indication of axon regeneration in  
2 the neuron.
- 1 10. The method of any one of claims 5, 7, and 8, wherein, after administration of the necrosis  
2 inhibitor and the apoptosis inhibitor, the neuron function of the CNS neuron is preserved or

3 improved relative to the neuron function prior to administration of the necrosis inhibitor and the  
4 apoptosis inhibitor.

1 11. The method of any one of claims 1-10, wherein the CNS neuron is selected from the group  
2 consisting of a sensory neuron, a motor neuron, a cortical neuron, a pyramidal neuron, a  
3 cerebellar neuron, a hippocampal neuron, and a midbrain neuron.

1 12. A method of promoting neuron function following injury to a CNS neuron, the method  
2 comprising:

3 reducing the production and/or activity of a RIP-1 kinase and/or a RIP-3 kinase in the  
4 CNS neuron thereby to promote CNS neuron function.

1 13. The method of claim 12, wherein the reduction in the production and/or activity of the  
2 RIP-1 kinase and/or the RIP-3 kinase is achieved by administering an effective amount of a  
3 RIP kinase inhibitor.

1 14. The method of claim 13, wherein after treatment with the RIP kinase inhibitor, the CNS  
2 neuron is capable of supporting axonal regeneration.

1 15. A method of promoting axon regeneration in a CNS neuron, the method comprising:

2 reducing the production and/or activity of a RIP-1 kinase and/or a RIP-3 kinase in the  
3 CNS neuron thereby to promote axon regeneration in a CNS neuron.

1 16. The method of claim 15, wherein the reduction in the production and/or activity of the  
2 RIP-1 kinase and/or the RIP-3 kinase is achieved by administering an effective amount of a  
3 RIP kinase inhibitor.

1 17. The method of any of claims 1-11, wherein the necrosis inhibitor is a necrostatin.

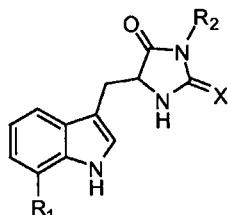
1 18. The method of claim 14 or 16, wherein the RIP kinase inhibitor is a necrostatin.

1 19. The method of claims 17 or 18, wherein the necrostatin is selected from the group  
2 consisting of necrostatin-1, necrostatin-2, necrostatin-3, necrostatin-4, necrostatin-5, and  
3 necrostatin-7, or a combination thereof.

1 20. The method of any one of claims 17-19, wherein from about 0.05 mg to about 2 mg of  
2 necrostatin is administered.

- 63 -

- 1 21. The method of any one of claims 1-11, wherein the apoptosis inhibitor is a pan-caspase
- 2 inhibitor.
- 1 22. The method of claim 21, wherein the pan-caspase inhibitor is zVAD, IDN-6556 or a
- 2 combination thereof.
- 1 23. The method of claim 21 or 22, wherein from about 0.15 mg to about 1.5 mg of the pan-
- 2 caspase inhibitor is administered.
- 1 24. The method of any one of claims 17-23, wherein the necrostatin, the apoptosis inhibitor, or
- 2 both the necrostatin and the apoptosis inhibitor are administered locally.
- 1 25. The method of any one of claims 17-23, wherein the necrostatin, the apoptosis inhibitor, or
- 2 both the necrostatin and the apoptosis inhibitor are administered systemically.
- 1 26. The method of any one of claims 17-25, wherein the necrostatin, the apoptosis inhibitor, or
- 2 both the necrostatin and the apoptosis inhibitor are administered sequentially or simultaneously.
- 1 27. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula
- 2 I:



5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein

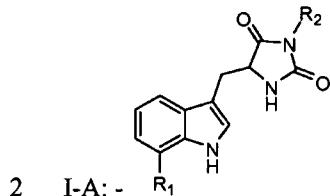
6 X is O or S;

7 R<sub>1</sub> is hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub> alkoxy, or halogen; and

8 R<sub>2</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl.

- 64 -

1 28. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula



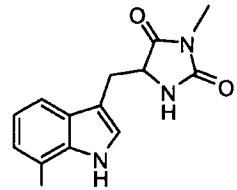
3 or a pharmaceutically acceptable salt, ester, or prodrug thereof,

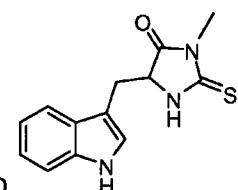
4 wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen and R<sub>2</sub> is H or an alkyl.

1 29. The method of any one of claims 17-26, wherein the necrostatin is a compound selected

2 from the group consisting of a compound of Formula I-B:  , or a

3 pharmaceutically acceptable salt, ester, or prodrug thereof; a compound of Formula I-C

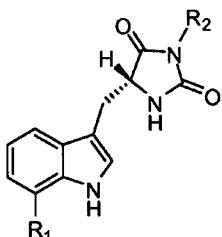
4  or a pharmaceutically acceptable salt, ester, or prodrug thereof; and a

5 compound of Formula I-D  or a pharmaceutically acceptable salt thereof.

1 30. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula

2 I-E:

- 65 -

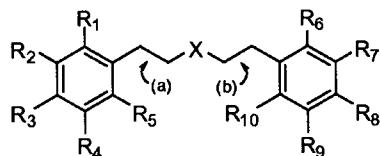


3

4 or a pharmaceutically acceptable salt, ester, or prodrug thereof,

5 wherein R<sub>1</sub> is H, alkyl, alkoxy, or a halogen and R<sub>2</sub> is H or an alkyl.

1 31. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
2 II:



3

4 (II)

5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6 X is -CH<sub>2</sub>-, -C(H)(R<sub>14</sub>)-, -C(=S)-, -C(=NH)-, or -C(O)-;

7 R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>4</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, R<sub>8</sub>, R<sub>9</sub>, and R<sub>10</sub> each represent independently hydrogen, acyl,  
8 acetyl, alkyl, halogen, amino, C<sub>1</sub>-C<sub>6</sub>alkoxy, nitro, -C(O)R<sub>12</sub>, -C(S)R<sub>12</sub>, -C(O)OR<sub>12</sub>,  
9 -C(O)NR<sub>12</sub>R<sub>13</sub>, -C(S)NR<sub>12</sub>R<sub>13</sub>, or -S(O<sub>2</sub>)R<sub>12</sub>;

10 R<sub>11</sub> is hydrogen, acyl, acetyl, alkyl, or acylamino;

11 R<sub>12</sub> and R<sub>13</sub> each represent independently hydrogen, an optionally substituted alkyl, an  
12 optionally substituted aryl, an optionally substituted heteroaryl, an optionally substituted  
13 aralkyl, or an optionally substituted heteroaralkyl;

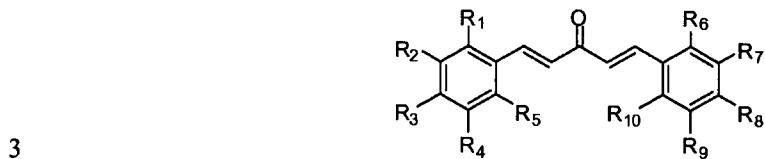
14 R<sub>14</sub> is acyl, acetyl, alkyl, halogen, amino, acylamino, nitro, -SR<sub>11</sub>, -N(R<sub>11</sub>)<sub>2</sub>, or -OR<sub>11</sub>;

15 the bond indicated by (a) can be a single or double bond; and

16 the bond indicated by (b) can be a single or double bond.

1 32. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
2 II-A:

- 66 -



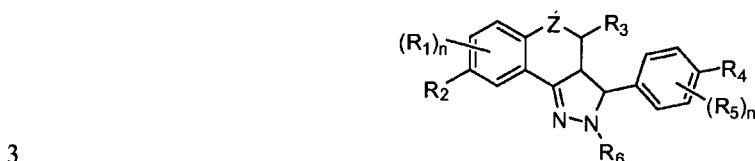
(II-A)

5 or a pharmaceutically acceptable salt thereof, wherein:

6 R<sub>1</sub>, R<sub>2</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, and R<sub>10</sub> each represent independently hydrogen, alkyl, halogen,  
7 amino, or methoxyl; and

8 R<sub>3</sub>, R<sub>4</sub>, R<sub>8</sub>, and R<sub>9</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxyl.

1 33. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
2 III:



(III)

5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6 Z is -CH<sub>2</sub>-, -CH<sub>2</sub>CH<sub>2</sub>-, -O-, -S-, -S(O)-, -S(O<sub>2</sub>)-, or -N(R<sub>7</sub>)-;

7 R<sub>1</sub>, R<sub>3</sub>, and R<sub>5</sub> each represent independently for each occurrence hydrogen, halogen,  
8 hydroxyl, amino, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkoxy, C<sub>1</sub>-C<sub>6</sub>alkoxy-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkanoyl, C<sub>1</sub>-  
9 C<sub>6</sub>alkylsulfinyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfinyl-C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl, C<sub>1</sub>-C<sub>6</sub>alkylsulfonyl-C<sub>1</sub>-  
10 C<sub>6</sub>alkyl, aryl, aralkyl, heterocycloalkyl, heteroaryl, or heteroaralkyl;

11 R<sub>2</sub> and R<sub>4</sub> are C<sub>1</sub>-C<sub>6</sub>alkoxy;

12 R<sub>6</sub> is -C(O)R<sub>8</sub>, -C(S)R<sub>8</sub>, -C(O)OR<sub>8</sub>, -C(O)NR<sub>8</sub>R<sub>9</sub>, -C(S)NR<sub>8</sub>R<sub>9</sub>, -C(NH)R<sub>8</sub>, or -S(O<sub>2</sub>)R<sub>8</sub>;

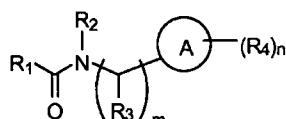
13 R<sub>7</sub> is alkyl, aralkyl, or heteroaralkyl;

14 R<sub>8</sub> and R<sub>9</sub> each represent independently hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, heteroalkyl, aryl,  
15 heteroaryl, aralkyl, or heteroaralkyl; and

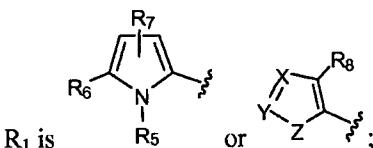
16 n represents independently for each occurrence 0, 1, or 2.

- 67 -

1 34. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
 2 IV:



or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:



R<sub>2</sub> and R<sub>3</sub> each represent independently for each occurrence hydrogen or methyl;

R<sub>4</sub> represents independently for each occurrence halogen, hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, C<sub>2</sub>-C<sub>6</sub>alkenyl, or C<sub>2</sub>-C<sub>4</sub>alkynyl;

R<sub>5</sub> is C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>6</sub> is hydrogen, halogen, or -CN;

R<sub>7</sub> is hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;

R<sub>8</sub> is C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>8</sub> taken together with R<sub>9</sub>, when present, forms a carbocyclic ring;

R<sub>9</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl, or R<sub>9</sub> taken together with R<sub>8</sub> forms a carbocyclic ring;

R<sub>10</sub> is hydrogen or C<sub>1</sub>-C<sub>6</sub>alkyl;

A is phenylene or a 5-6 membered heteroarylene;

X is N or -C(R<sub>9</sub>)-;

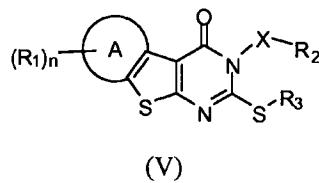
Y is N or -C(R<sub>10</sub>)-;

Z is S or O; and

m and n each represent independently 1, 2, or 3.

1 35. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
 2 V:

- 68 -



4

(V)

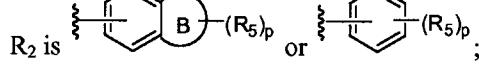
5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6 A is a saturated or unsaturated 5-6 membered carbocyclic ring;

7 X is a bond or C<sub>1</sub>-C<sub>4</sub>alkylene;

8 R<sub>1</sub> is C<sub>1</sub>-C<sub>6</sub> alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or  
9 C(O)N(R<sub>4</sub>)<sub>2</sub>;

THE BOSTONIAN



10

11 R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN, -CN, C<sub>1</sub>-C<sub>6</sub>alkyl, or C<sub>2</sub>-C<sub>6</sub>alkenyl;

12 R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;

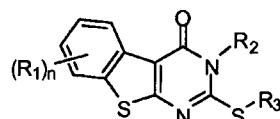
13 R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-

14 C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;

15 B is a 5-6 membered heterocyclic or carbocyclic ring; and

16 n and p each represent independently 0, 1, or 2.

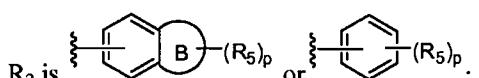
1 36. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
2 V-A:



(V-A)

5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6  $R_1$  is  $C_1$ - $C_6$ alkyl, halogen, hydroxyl,  $C_1$ - $C_6$ alkoxyl, or  $-N(R_4)_2$ ;

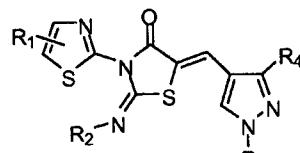


7

- 69 -

8        R<sub>3</sub> is -C<sub>1</sub>-C<sub>6</sub>alkylene-CN;  
 9        R<sub>4</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;  
 10      R<sub>5</sub> represents independently for each occurrence C<sub>1</sub>-C<sub>6</sub>alkyl, halogen, hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>4</sub>)<sub>2</sub>, -C(O)R<sub>4</sub>, CO<sub>2</sub>R<sub>4</sub>, or C(O)N(R<sub>4</sub>)<sub>2</sub>;  
 12      B is a 5-6 membered heterocyclic or carbocyclic ring; and  
 13      n and p each represent independently 0, 1, or 2.

1        37. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
 2        VII:



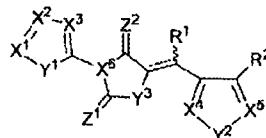
3  
 4        (VII)

5        or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:  
 6        R<sub>1</sub>, R<sub>2</sub>, and R<sub>3</sub> each represent independently hydrogen or C<sub>1</sub>-C<sub>4</sub>alkyl;

7        R<sub>4</sub> is ;  
 8        R<sub>5</sub> and R<sub>6</sub> each represent independently for each occurrence halogen, C<sub>1</sub>-C<sub>6</sub>alkyl,  
 9        hydroxyl, C<sub>1</sub>-C<sub>6</sub>alkoxyl, -N(R<sub>7</sub>)<sub>2</sub>, -NO<sub>2</sub>, -S-C<sub>1</sub>-C<sub>6</sub>alkyl, -S-aryl, -SO<sub>2</sub>-C<sub>1</sub>-C<sub>6</sub>alkyl, -SO<sub>2</sub>-aryl,  
 10      -C(O)R<sub>7</sub>, -CO<sub>2</sub>R<sub>7</sub>, -C(O)N(R<sub>7</sub>)<sub>2</sub>, heterocycloalkyl, aryl, or heteroaryl;  
 11      R<sub>7</sub> represents independently for each occurrence hydrogen, C<sub>1</sub>-C<sub>6</sub>alkyl, aryl, or aralkyl;  
 12      or two occurrences of R<sub>7</sub> attached to the same nitrogen atom are taken together with the  
 13      nitrogen atom to which they are attached to form a 3-7 membered heterocyclic ring;  
 14      A is a 5-6 membered heterocyclic ring; and  
 15      p is 0, 1, or 2.

1        38. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula  
 2        VIII:

- 70 -



3

4

(VIII)

5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6 each  $X^1$ ,  $X^2$ ,  $X^3$ ,  $X^4$ ,  $X^5$ , and  $X^6$  is selected, independently, from N or  $CR^{X1}$ ;

7 each  $Y^1$ ,  $Y^2$ , and  $Y^3$  is selected, independently, from O, S,  $NR^{Y1}$ , or  $CR^{Y2}R^{Y3}$ ;

8 each  $Z^1$  and  $Z^2$  is selected, independently, from O, S, or  $NR^{Z1}$ ;

9 each  $R^{Y1}$  and  $R^{Z1}$  is selected, independently, from H, optionally substituted  $C_1$ .

10  $\epsilon$ alkyl, optionally substituted  $C_2$ -alkenyl, optionally substituted  $C_2$ -alkynyl, optionally

11 substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl,

12 optionally substituted heteroaryl,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ , or  $-C(=O)NR^{5A}R^{6A}$ ;

13 each  $R^{X1}$ ,  $R^{Y2}$ , and  $R^{Y3}$  is selected, independently, from H, halogen, CN, NC,  $NO_2$ ,  $N_3$ ,

14  $OR^3$ ,  $SR^3$ ,  $NR^3R^4$ ,  $-C(=O)R^{5A}$ ,  $-C(=O)OR^{5A}$ ,  $-C(=O)NR^{5A}R^{6A}$ ,  $-S(=O)R^{5A}$ ,  $-S(=O)_2R^{5A}$ , -

15  $S(=O)_2OR^{5A}$ ,  $-S(=O)_2NR^{5A}R^{6A}$ , optionally substituted  $C_1$ -alkyl, optionally substituted  $C_2$ ,

16  $\epsilon$ alkenyl, optionally substituted  $C_2$ -alkynyl, optionally substituted cycloalkyl, optionally

17 substituted heterocyclyl, optionally substituted aryl, or optionally substituted heteroaryl;

18 each  $R^1$ ,  $R^2$ ,  $R^{5A}$ ,  $R^{5B}$ ,  $R^{6A}$ , and  $R^{6B}$  is selected from H, optionally substituted  $C_1$ -alkyl,

19 optionally substituted  $C_2$ -alkenyl, optionally substituted  $C_2$ -alkynyl, optionally substituted

20 cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl, or optionally

21 substituted heteroaryl; or  $R^{5A}$  and  $R^{6A}$ , or  $R^{5B}$  and  $R^{6B}$  combine to form a heterocyclyl; and

22 each  $R^3$  and  $R^4$  is selected from H, optionally substituted  $C_1$ -alkyl, optionally

23 substituted cycloalkyl, optionally substituted heterocyclyl, optionally substituted aryl,

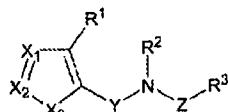
24 optionally substituted heteroaryl,  $-C(=O)R^{5B}$ ,  $-C(=S)R^{5B}$ ,  $-C(=NR^{6B})R^{5B}$ ,  $-C(=O)OR^{5B}$ ,

25  $-C(=O)NR^{5B}R^{6B}$ ,  $-S(=O)R^{5B}$ ,  $-S(=O)_2R^{5B}$ ,  $-S(=O)_2OR^{5B}$ , or  $-S(=O)_2NR^{5B}R^{6B}$ .

1 39. The method of any one of claims 17-26, wherein the necrostatin is a compound of Formula

2 IX:

- 71 -



5 or a pharmaceutically acceptable salt, ester, or prodrug thereof, wherein:

6 X<sub>1</sub> and X<sub>2</sub> are, independently, N or CR<sup>4</sup>;

7 X<sub>3</sub> is selected from O, S, NR<sup>5</sup>, or —(CR<sup>5</sup>)<sub>2</sub>;

8 Y is selected from C(O) or CH<sub>2</sub>; and

9 Z is (CR<sup>6</sup>R<sup>7</sup>)<sub>n</sub>;

10 R<sup>1</sup> is selected from H, halogen, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted C<sub>1-6</sub>cycloalkyl, or optionally substituted aryl;

11 R<sup>2</sup> is selected from H or optionally substituted C<sub>1-6</sub>alkyl;

12 R<sup>3</sup> is optionally substituted aryl;

13 each R<sup>4</sup> is selected from H, halogen, carboxamido, nitro, cyano, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted aryl;

14 R<sup>5</sup> is selected from H, halogen, optionally substituted C<sub>1-6</sub>alkyl, or optionally substituted aryl;

15 each R<sup>6</sup> and R<sup>7</sup> is, independently, selected from H, optionally substituted C<sub>1-6</sub>alkyl, or aryl; and

16 n is 0, 1, 2, or 3.

1 40. A composition for use in promoting axon regeneration in a CNS neuron comprising: a  
2 pharmaceutically acceptable carrier, a necrosis inhibitor and an apoptosis inhibitor.

1 41. The composition of claim 40, wherein the necrosis inhibitor is a necrostatin selected from  
2 the group consisting of necrostatin-1, necrostatin-2, necrostatin-3, necrostatin-4, necrostatin-5,  
3 and necrostatin-7, or a combination thereof.

1 42. The composition of claim 40 or 41, wherein the necrostatin is an (R)-enantiomer of  
2 necrostatin-1.

- 72 -

- 1    43. The composition of any one of claims 40-42, wherein the apoptosis inhibitor is a pan-  
2    caspase inhibitor.
  
- 1    44. The composition of claim 43, wherein the pan-caspase inhibitor is selected from the group  
2    consisting of ZVAD, IDN-6556, and a combination of ZVAD and IDN-6556.

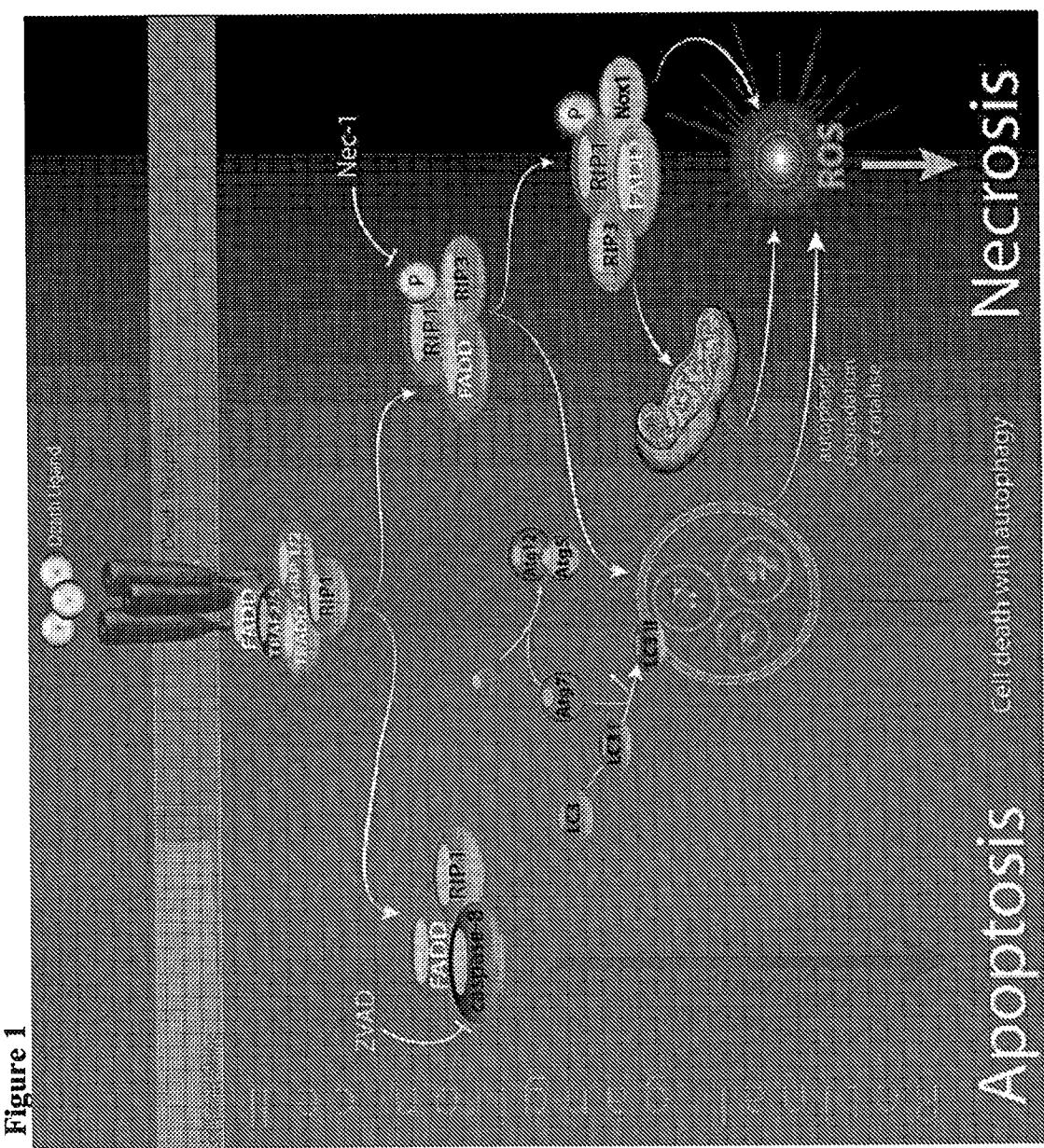


Figure 1

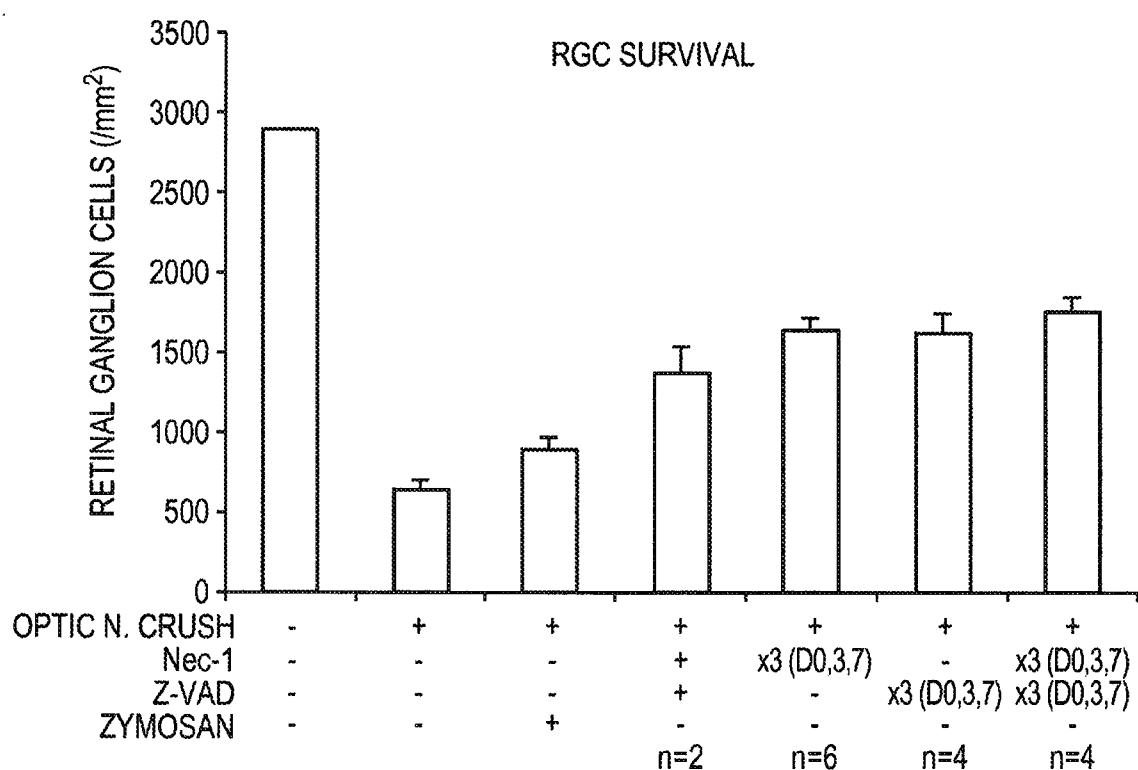
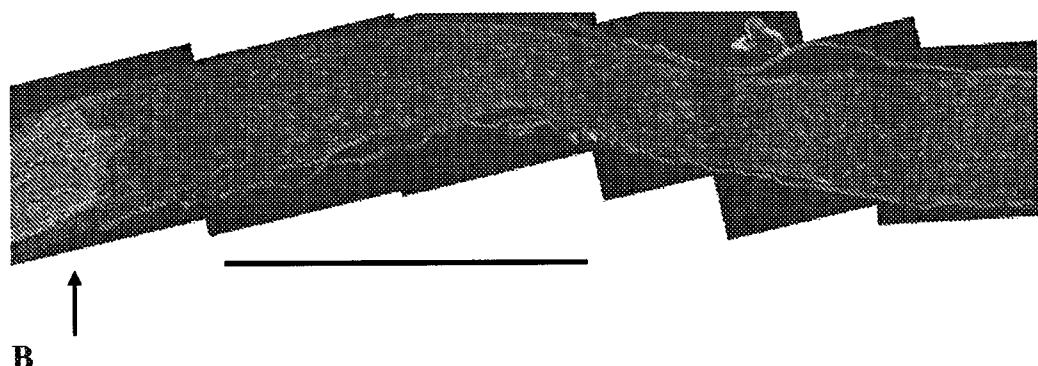
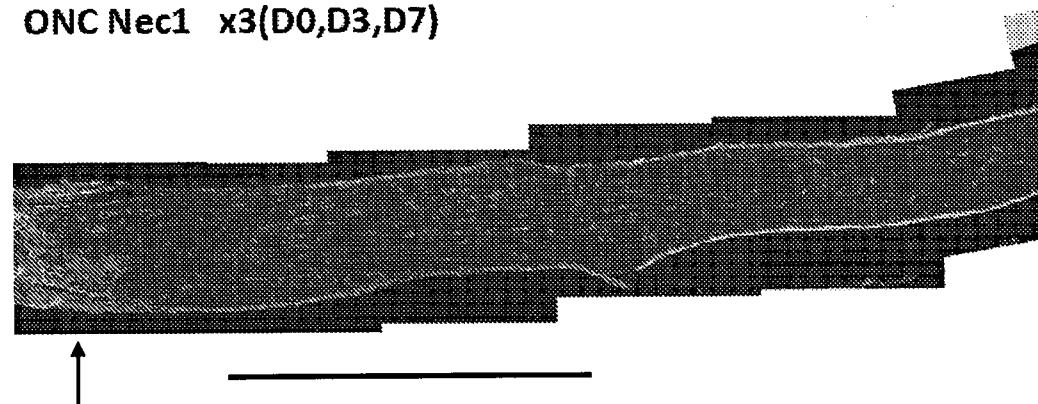
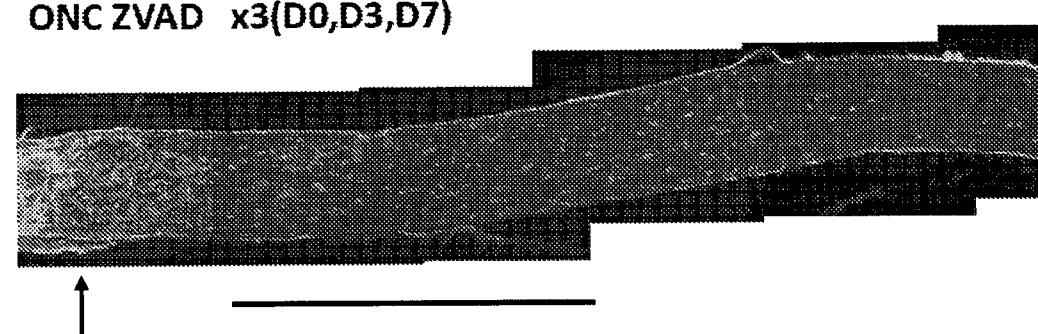
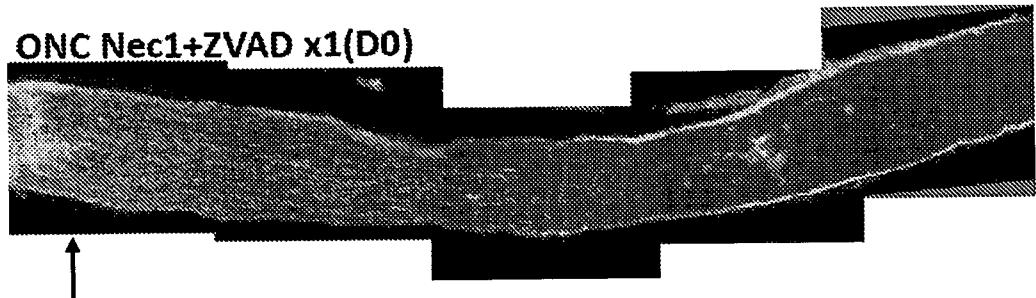
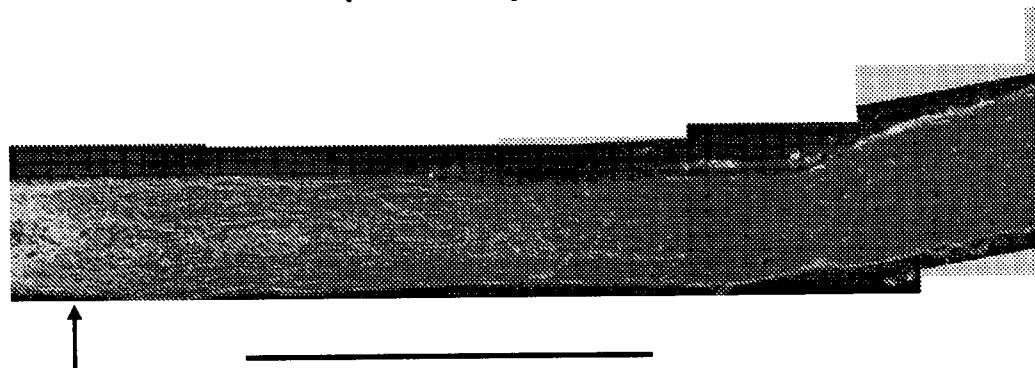


FIG. 2

**Figure 3****A****ONC****B****ONC Nec1 x3(D0,D3,D7)****C****ONC ZVAD x3(D0,D3,D7)**

**Figure 3 (continued)****D****ONC Nec1+ZVAD x1(D0)****E****ONC Nec1+ZVAD x3(D0,D3,D7)**

## 摘要

本發明提供用於促進中樞神經系統（CNS）的神經元的軸突再生，促進損傷後到的 CNS 神經元的神經功能，例如，腦和/或脊髓損傷的方法。軸突再生中的 CNS 神經元或神經功能損傷後到中樞神經系統的神經元可以通過施用壞死抑制劑單獨或與凋亡抑制劑以患有 CNS 障礙，其中所述中樞神經系統病症的症狀是軸突促進變性。