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(54) Title: NRF2 SCREENING ASSAYS AND RELATED METHODS AND COMPOSITIONS

(57) Abstract: Provided are certain methods of screening, identifying, and evaluating neuroprotective compounds useful for treatment of neurological diseases, such as, e.g., multiple sclerosis (MS). The compounds described upregulate the cellular cytoprotective pathway regulated by Nrf2. Also provided are certain methods of utilizing such compounds in therapy for neurological disease, particularly, for slowing or reducing demyelination, axonal loss, or neuronal and oligodendrocyte death.

Nrf2 SCREENING ASSAYS AND RELATED METHODS AND COMPOSITIONS

[0001] Provided are certain compounds for treating neurological diseases, including demyelinating neurological diseases, such as, e.g., multiple sclerosis.

[0002] Multiple sclerosis (MS) is an autoimmune disease with the autoimmune activity directed against central nervous system (CNS) antigens. The disease is characterized by inflammation in parts of the CNS, leading to the loss of the myelin sheathing around neuronal axons (demyelination), loss of axons, and the eventual death of neurons, oligodendrocytes and glial cells.

[0003] An estimated 2,500,000 people in the world suffer from MS. It is one of the most common diseases of the CNS in young adults. MS is a chronic, progressing, disabling disease, which generally strikes its victims some time after adolescence, with diagnosis generally made between 20 and 40 years of age, although onset may occur earlier. The disease is not directly hereditary, although genetic susceptibility plays a part in its development. Relapsing-remitting MS presents in the form of recurrent attacks of focal or multifocal neurologic dysfunction. Attacks may occur, remit, and recur, seemingly randomly over many years. Remission is often incomplete and as one attack follows another, a stepwise downward progression ensues with increasing permanent neurological deficit.

[0004] Although various immunotherapeutic drugs can provide relief in patients with MS, none is capable of reversing disease progression, and some can cause serious adverse effects. Most current therapies for MS are aimed at the reduction of inflammation and suppression or modulation of the immune system. As of 2006, the available treatments for MS reduce inflammation and the number of new episodes but not all have an effect on disease progression. A number of clinical trials have shown that the suppression of inflammation in chronic MS rarely significantly limits the accumulation of disability through sustained disease progression, suggesting that neuronal damage and inflammation are independent pathologies. Promoting CNS remyelination as a repair mechanism and otherwise preventing axonal loss and

neuronal death are some of the important goals for the treatment of MS. For a comprehensive review of MS and its current therapies, see, e.g., McAlpine's Multiple Sclerosis, by Alastair Compston et al., 4th edition, Churchill Livingstone Elsevier, 2006.

[0005] "Phase 2 enzymes" serve as a protection mechanism in mammalian cells against oxygen/nitrogen species (ROS/RNS), electrophiles and xenobiotics. These enzymes are not normally expressed at their maximal levels and, their expression can be induced by a variety of natural and synthetic agents. Nuclear factor E2-related factor 2 (Nrf2) is a transcription factor responsible for the induction of a variety of important antioxidant and detoxification enzymes that coordinate a protective cellular response to metabolic and toxic stress.

[0006] ROS/RNS are most damaging in the brain and neuronal tissue, where they attack post-mitotic (i.e., non-dividing) cells such as glial cells, oligodendocytes, and neurons, which are particularly sensitive to free radicals. This process leads to neuronal damage. Oxidative stress has been implicated in the pathogenesis of a variety of neurodegenerative diseases, including ALS, Alzheimer's disease (AD), and Parkinson's disease (PD). For review, see, e.g., van Muiswinkel et al., *Curr. Drug Targets CNS--Neurol. Disord.*, 2005, 4:267-281. An anti-oxidative enzyme under control of Nrf2, NQO1 (NAD(P)H dehydrogenase, quinone (1)), was recently reported to be substantially upregulated in the brain tissues of AD and PD subjects (Muiswinkel et al., *Neurobiol. Aging*, 2004, 25: 1253). Similarly, increased expression of NQO1 was reported in the ALS subjects' spinal cord (Muiswinkel et al., *Curr. Drug Targets--CNS. Neurol. Disord.*, 2005, 4:267-281) and in active and chronic lesions in the brains of patients suffering from MS (van Horssen et al., *Free Radical Biol. & Med.*, 2006, 41 311-311). These observations indicate that the Nrf2 pathway may be activated in neurodegenerative and neuroinflammatory diseases as an endogenous protective mechanism. Indeed, most recently, it has been reported that induced activation of Nrf2-dependent genes by certain cyclohexanone-based compounds (NEPP) counters the toxic effects of metabolic inhibition and ROS/RNS production in

the brain and protects neurons from death in vitro and in vivo (see Satoh et al., PNAS, 2006, 103(3):768-773).

[0007] Additionally, many publications have reported neuroprotective effects of compounds in natural plant-derived compounds ("phytochemicals"), including α -tocopherol (vitamin E), lycopene (tomatoes), resveratrol (red grapes), sulforaphane (broccoli), EGCG (green tea), etc. For review, see Mattson and Cheng, Trends in Neurosci., 2006, 29(11):632-639. Originally, the action of these compounds was attributed to their anti-oxidant properties. However, while most anti-oxidants are effective only at high concentrations, at least some of these compounds appear to exert neuroprotective effects at much lower doses. Emerging evidence suggests that these compounds may exert their neuroprotective effects by activating cellular stress-response pathways, including the Nrf2 pathway, resulting in the upregulation of neuroprotective genes. However, the exact mechanism of action of these compounds remains poorly understood.

[0008] To date, more than 10 different chemical classes of inducers of Nrf2 pathway have been identified including isothiocyanates and their thiol addition products, dithiocarbamates, as well as 1,2-dithiole-3-thiones, trivalent arsenic derivatives (e.g., phenyl arsenoxide), heavy metals, certain conjugated cyclic and acyclic polyenes (including porphyrins, chlorophyllins, and chlorophyll), and vicinal dimercaptans. These inducers have few structural similarities. They are mostly electrophiles, and all can react chemically with thiol groups by alkylation, oxidation, or reduction, suggesting that the intracellular sensor for inducers is likely to contain very highly reactive (cysteine) thiols. The inducers can modify thiol groups by a variety of mechanisms including: alkylation (Michael addition acceptors, isothiocyanates, quinones); oxidation (e.g., peroxides and hydroperoxides); and direct reaction with thiol/disulfide linkages (e.g., vicinal dithiols such as 1,2-dimercaptopropanol, lipoic acid). These diverse response mechanisms provide plasticity for cellular responses to a variety of electrophilic and oxidant stressors.

[0009] Provided are methods that comprise at least one of the following methods:

- 1) methods of screening for at least one new candidate compound for treating a neurological disease;
- 2) methods of evaluating neuroprotective properties of at least one drug candidate for treating a neurological disease;
- 3) methods of comparing (e.g., for bioequivalence) at least two pharmaceutical compositions which comprise fumaric acid derivatives;
- 4) methods of treating a neurological disease by administering to the subject in need thereof at least one compound that is partially structurally similar to DMF or MMF; and
- 5) methods of treating a neurological disease by a combination therapy that comprises administration of at least one first compound that upregulates the Nrf2 pathway and at least one second compound that does not upregulate the Nrf2 pathway.

[0010] In some embodiments, the neurological disease is a neurodegenerative disease such as, for example, ALS, Parkinson's disease, Alzheimer's disease, and Huntington's disease. In some embodiments the neurological disease is MS or another demyelinating neurological disease.

[0011] In some embodiments, the methods 1-3 further comprise:

- a) contacting a cell with the test compound, and
- b) determining whether the Nrf2 pathway is upregulated in the cell.

In some embodiments, the methods may further comprise:

- c) determining whether the test compound slows or prevents demyelination, axonal loss, and/or neuronal death, and/or
- d) selecting the test compound as a candidate for treating neurodegeneration in a neurological disease if 1) the Nrf2 pathway is upregulated and 2) demyelination, axonal loss, and/or neuronal death are/is prevented or slowed.

[0012] In some embodiments, the methods 1-3 comprise contacting a cell with at least one test compound and determining whether the Nrf2 pathway is upregulated in the cell. In such methods, an upregulation of the Nrf2 pathway above a threshold

(e.g., by at least 30% over a control) indicates that the at least one compound has at least one biological property beneficial in treating a neurological disease (e.g., neuroprotective properties). In some embodiments, the upregulation of the Nrf2 pathway is assessed (in vivo and/or in vitro) by at least one of the following:

- i) expression levels of endogenously produced and/or exogenously introduced Nrf2;
- ii) subcellular localization and/or nuclear translocation of Nrf2;
- iii) expression levels and/or activity of one or more genes under control of Nrf2 (e.g., endogenous NQO1) or an Nrf2-regulated reporter gene in an artificial reporter construct;
- iv) levels of Nrf2 binding to the Nrf2-binding DNA element ARE;
- v) stability of Nrf2/Keap1 complexes; and
- vi) modification (e.g., alkylation) levels of Keap1 and/or at least one other Nrf2/Keap1-associated proteins.

[0013] In some embodiments of methods 1-3, the compounds that are being screened, evaluated, or compared comprise at least one member of at least one of the following classes of compounds: mild alkylating agents, Michael addition acceptors, and compounds that are metabolized upon administration to Michael addition acceptors. In some embodiments, the Michael addition acceptor has the structure of Formula I, II, III, or IV set forth below.

[0014] In some embodiments method 1 comprises:

- a) contacting a cell with a plurality of test compounds,
- b) determining whether the Nrf2 pathway is upregulated in the cell, and
- c) selecting from the plurality of compounds at least one compound that upregulates the Nrf2 pathway,

wherein an upregulation of the Nrf2 pathway by the selected at least one compound indicates that the selected at least one compound may be useful for treating a neurological disease. The plurality of compounds may be represented, e.g., by a combinatorial chemical library, and the method may be performed, e.g., by high-throughput screening.

[0015] In some embodiments method 2 comprises:

- a) contacting a cell with the at least one drug or drug candidate, and
- b) determining whether the Nrf2 pathway is upregulated in the cell,

wherein an upregulation of the Nrf2 pathway by the at least one drug or drug candidate indicates that the at least one drug or drug candidate is useful for neuroprotection in treating a human having a neurological disease.

[0016] In some embodiments method 3 comprises:

- a) contacting a cell with a first composition comprising at least one test compound, and
- b) comparing the level of Nrf2 pathway upregulation in the cell by the at least one test compound to the corresponding level of the Nrf2 pathway upregulation in a control cell treated with a second composition comprising at least one of DMF and MMF.

[0017] In some embodiments of method 3, the test compound is fumaric acid, a salt thereof, or a fumaric acid derivative. In some embodiments, the first composition comprises DMF, MMF, or both. In some embodiments, the dose and/or the formulation of the first composition differs from the dose and/or the formulation of the second composition.

[0018] In some embodiments, method 3 further comprises:

- c) comparing at least one pharmacokinetic parameter (e.g., serum-half-life) of the first and the second compositions.

[0019] In some embodiments method 4 comprises administering to the mammal a therapeutically effective amount of at least one neuroprotective compound having Formula I, II, III, or IV, e.g., a fumaric acid derivative (e.g., DMF or MMF).

[0020] In some embodiments method 4 provides a method of slowing or preventing neurodegeneration in a patient in need thereof, by administering the compound in an amount and for a period of time sufficient to slow or prevent demyelination, axonal loss, and/or neuronal death, e.g., by at least 30% relative to a control.

[0021] In some embodiments method 5 comprises:

- a) administering to the mammal a therapeutically effective amount of at least one first compound that upregulates the Nrf2 pathway, and
- b) administering a therapeutically effective amount of at least one second compound that does not upregulate the Nrf2 pathway.

[0022] In some embodiments of method 5, the at least one first compound, used in step (a), is a compound of Formula I, II, III, or IV, e.g., a fumaric acid derivative (e.g., DMF or MMF); and the at least one second compound, which is used in step (b), is an immunosuppressive or an immunomodulatory compound that does not upregulate the Nrf2 pathway (e.g., by more than 30% over a control).

[0023] In some embodiments method 5 comprises administering to the mammal a therapeutically effective amount of a compound of Formula I, II, III, or IV.

[0024] In some embodiments of methods 1-5, the at least one compound being screened, identified, evaluated, or used for treating a neurological disorder is not fumaric acid or its salt, or a fumaric acid derivative (e.g., DMF or MMF).

[0025] Other features and embodiments of the invention will be apparent from the following description and the claims.

BRIEF DESCRIPTION OF THE FIGURES

[0026] Figure 1 demonstrates that DMF and MMF are activators of Nrf2 at concentrations within clinical exposure range (cells in culture).

[0027] Figure 2 shows results of RNAi experiments.

[0028] Figure 3 shows evidence of Nrf2 activation by DMF and MMF In vivo.

[0029] Figure 4 shows evidence of Nrf2 activation by DMF and MMF In vivo.

[0030] Fumaric acid esters, such as DMF, have been proposed for treatment of MS (see, e.g., Schimrigk et al., Eur. J. Neurol., 2006, 13(6):604-10; Drugs R&D, 2005, 6(4):229-30).

[0031] Provided are, among other things, means for identifying compounds with a new therapeutic modality useful in at least one of multiple neurological indications and, optionally, complementary to other drugs for the treatment of a neurological disease, including a number of currently used immunomodulators.

[0032] DMF is a member of a large group of anti-oxidant molecules known for their cytoprotective and anti-inflammatory properties. These molecules also share the property of the Nrf2 pathway activation. Thus, the finding that DMF activates the Nrf2 pathway in conjunction with the neuroprotective effects of DMF further offers a rationale for identification of structurally and/or mechanistically related molecules that would be expected to be therapeutically effective for the treatment of neurological disorders, such as, e.g., MS.

[0033] Certain terms are defined in this section; additional definitions are provided throughout the description.

[0034] The terms "activation" and "upregulation," when used in reference to the Nrf2 pathway, are used interchangeably herein.

[0035] The terms "disease" and "disorder" are used interchangeably herein.

[0036] The term "a drug for treating a neurological disease" refers to a compound that has a therapeutic benefit in a specified neurological disease as shown in at least one animal model of a neurological disease or in human clinical trials for the treatment of a neurological disease.

[0037] The term "neuroprotection" and its cognates refer to prevention or a slowing in neuronal degeneration, including, for example, demyelination and/or axonal loss, and/or, neuronal and/or oligodendrocyte death. Neuroprotection may occur through several mechanisms, e.g., through reducing inflammation, providing neurotrophic factors, scavenging free radicals, etc. As used herein, a compound is considered neuroprotective if it (1) upregulates the Nrf2 pathway above a certain threshold and (2) provides neuroprotection, regardless of possible other mechanisms of action.

[0038] The terms "treatment," "therapeutic method," "therapeutic benefits," and the like refer to therapeutic as well as prophylactic/preventative measures. Thus, those in need of treatment may include individuals already having a specified disease and those who are at risk for acquiring that disease.

[0039] The terms "therapeutically effective dose" and "therapeutically effective amount" refer to that amount of a compound which results in at least one of prevention

or delay of onset or amelioration of symptoms of a neurological disorder in a subject or an attainment of a desired biological outcome, such as reduced neurodegeneration (e.g., demyelination, axonal loss, and neuronal death) or reduced inflammation of the cells of the CNS.

[0040] In one aspect, provided are methods of evaluating neuroprotective properties of test compounds, including the following methods:

- 1) methods of screening for new candidate compounds that may be useful for treating a neurological disease;
- 2) methods of evaluating neuroprotective properties of drugs and candidates that are used or proposed for treating a neurological disease;
- 3) methods of comparing (e.g., for bioequivalence) two or more pharmaceutical compositions which contain fumaric acid derivatives;

[0041] In some embodiments, methods 1-3 may comprise:

- a) contacting a cell with the test compound,
- b) determining whether the Nrf2 pathway is upregulated in the cell,

and, in some embodiments, additionally performing the following step(s):

- c) determining whether the test compound slows or prevents demyelination, axonal loss, and/or neuronal death, and/or
- d) selecting the test compound as a candidate for treating neurodegeneration in a neurological disease if 1) the Nrf2 pathway is upregulated and 2) demyelination, axonal loss, and/or neuronal death are/is prevented or slowed.

Method 1

[0042] In some embodiments the methods of screening for a candidate compound for treating a neurological disease comprise:

- a) contacting a cell with a plurality of test compounds,
- b) determining whether the Nrf2 pathway is upregulated in the cell, and
- c) selecting from the plurality of compounds at least one compound that upregulates the Nrf2 pathway,

wherein an upregulation of the Nrf2 pathway by the selected at least one compound indicates that the selected at least one compound may be useful for treating a neurological disease. For example, the plurality of compounds may be represented by a combinatorial chemical library, and the screening method may be performed by a high-throughput screening as described in, e.g., High-Throughput Screening in Drug Discovery (Methods and Principles in Medicinal Chemistry), by Jörg Hüser (ed.), John Wiley & Sons (2006).

[0043] Combinatorial libraries of compounds are also described in, e.g., Solid-Supported Combinatorial and Parallel Synthesis of Small-Molecular-Weight Compound Libraries (Tetrahedron Organic Chemistry) Ian Salusbury (ed.), Elsevier (1998); Combinatorial Libraries: Synthesis, Screening and Application Potential (Library Binding), by Riccardo Cortese (ed.), Walter de Gruyter (1995). The libraries of compounds may be, for example, quinone libraries and other libraries as described in Mittoo, Comb. Chem. & High Throughput Screen, 2006, 9:421-423.

[0044] In some embodiments, the at least one compound or plurality of compounds being screened and/or selected comprises at least one compound selected from at least one of the following groups of compounds: mild alkylating agents, Michael addition acceptors or compounds that are metabolized to Michael addition acceptors, including compounds of Formulas I, II, III, or IV.

[0045] In some of the embodiments, the at least one compound is selected from fumaric acid, its salts, and fumaric acid derivatives.

Method 2

[0046] Also provided are methods of evaluating neuroprotective properties of at least one drug or drug candidate for treating at least one neurological disease. Such methods comprise:

- a) contacting a cell with the at least one drug or drug candidate, and
- b) determining whether the Nrf2 pathway is upregulated in the cell,

wherein the upregulation of the Nrf2 pathway by the at least one drug or drug candidate indicates that the at least one drug or drug candidate is neuroprotective in treating a human having a neurological disease.

[0047] In some embodiments, the upregulation of the Nrf2 pathway by the at least one drug or drug candidate indicates that the at least one drug or drug candidate has at least one activity selected from slowing demyelination, slowing the loss of axons, and slowing the rate of neuronal death.

[0048] In some embodiments, the method of evaluating at least one drug or drug candidate comprises an additional step:

c) evaluating demyelination, loss of axons, and/or neuronal death.

[0049] In some embodiments, steps a) and c) are performed in vivo in at least one model of a neurological disease, e.g., as described below.

[0050] In other embodiments, particularly those in which the neurological disease is multiple sclerosis or another demyelinating disease, the evaluated at least one drug or drug candidate for a neurological disease is chosen from the following: FTY720 (2-(4-octylphenethyl)-2-aminopropane-1,3-diol; Novartis); anti-IL12 antibody (e.g., ABT-874; Abbott Laboratories); GSK683699 (GSK/Tanabe); NeuroVax (Immune Response Corp.; Darlington, Curr. Opin. Mol. Ther., 2005, 7(6):598-603); anti-CCR2 antibody (e.g., MLN 1202; Millennium); interferon β -1a (e.g., Avonex®; Biogen Idec); anti- α 4-integrin antibody (e.g., Tysabri®; Biogen Idec/Elan); anti-CD20 antibody (e.g., Rituxan® (Biogen Idec/Genentech); TV 5010 (Teva); NBI-788 (Neurocrine); MBP8298 (BioMS (see Warren et al., Eur. J. Neurol., 2006, 13(8):887-95); Mylinax (Oral Cladribine; 2-chlorodeoxyadenosine; Serono/IVAX); Teriflunomide ((Z)-2-cyano-N-(4-(trifluoromethyl)phenyl)-3-hydroxybut-2-enamide; Sanofi-Aventis); Tamsulosin (Wyeth); Laquinimod (5-chloro-N-ethyl-1,2-dihydro-4-hydroxy-1-methyl-2-oxo-N-phenylquinoline-3-carboxamide; Active Biotech/Teva); and interferon tau (Tauferon; Pepgen).

[0051] In some embodiments, the at least one drug or drug candidate being evaluated is at least one compound selected from at least one class selected from a mild alkylating agent, a Michael addition acceptor, and a compound that is metabolized to a Michael addition acceptor, including compounds of Formulas I, II, III, or IV.

[0052] In some of the embodiments, the compound is fumaric acid, its salt, or a fumaric acid derivative.

Method 3

[0053] Also provided are methods of comparing (e.g., for bioequivalence) at least two pharmaceutical compositions. Such methods comprise:

- a) contacting a cell with at least one first composition comprising a test compound, and
- b) comparing the level of the Nrf2 pathway upregulation in the cell by the test compound to the corresponding level of the Nrf2 pathway upregulation in a cell treated with at least one second composition ("comparator composition") comprising DMF, MMF, or both.

[0054] In some embodiments, substantially dissimilar levels of upregulation by the at least one first and at least one second compositions indicate that the compositions are not bioequivalent.

[0055] In some embodiments, the test compound is fumaric acid, its salt thereof, a fumaric acid derivative, or mixtures thereof. In some embodiments, the first composition comprises at least one of DMF, MMF, and both DMF and MMF. In some embodiments, the dose and/or the formulation of the at least one first composition differs from the dose and/or the formulation of the at least one second composition. The at least one first composition may be a controlled release composition such as, e.g., compositions described in WO 2006/037342.

[0056] In some embodiments, the method further comprises an additional step:

- c) comparing at least one pharmacokinetic parameter of the at least one first and the at least one second compositions.

[0057] Pharmacokinetic parameters and methods for evaluating the same are well known and are described in, e.g., Pharmacokinetics, Second Edition (Drugs and the Pharmaceutical Sciences) by Milo Gibaldi et al. (eds.), Informa Healthcare (1982). Examples of such pharmacokinetic parameters that can be evaluated include serum half-life, clearance, and volume distribution.

[0058] In some embodiments, substantially dissimilar pharmacokinetic parameter(s) of the at least one first and at least one second compositions indicate that the compositions are not bioequivalent.

[0059] In some embodiments, the test compound being evaluated is a mild alkylating agent, and more specifically, a Michael addition acceptor, or a compound that is metabolized to a Michael addition acceptor.

[0060] In some of the embodiments, the test compound is fumaric acid or its salt, or a fumaric acid derivative.

[0061] Also provided are methods of treating a mammal who has or is at risk for developing a neurological disease, including the following methods:

- 4) methods of treating a neurological disease by administering to the subject in need thereof at least one compound that is partially structurally similar to DMF or MMF (including compounds selected using methods 1-3 described above) ; and
- 5) methods of treating a neurological disorder by a combination therapy that includes administration of a first compound that does not upregulate the Nrf2 pathway and a second compound that upregulates the Nrf2 pathway.

Method 4

[0062] Also provided are methods of treating a neurological disease by administering to the subject in need thereof at least one compound that is at least partially structurally similar to DMF and/or MMF.

[0063] In some embodiments of method 4, a method of treating a mammal who has or is at risk for a neurological disease is provided. The method comprises administering to the mammal a therapeutically effective amount of at least one neuroprotective compound which has Formula I, II, III, or IV, e.g., a fumaric acid derivative (e.g., DMF or MMF).

[0064] In some embodiments of method 4, a method of slowing or preventing neurodegeneration (more specifically, e.g., demyelination, axonal loss, and/or neuronal death) in a subject in need thereof, by administering the at least one compound in an amount and for a period of time sufficient to do at least one of slow or

prevent demyelination, slow or prevent axonal loss, and slow or prevent neuronal death, e.g., by at least 30%, 50%, 100% or higher over a control over a period of at least 5, 10, 12, 20, 40, 52, 100, or 200 weeks, or more.

Method 5

[0065] Also provided are methods of treating a mammal having a neurological disease by combination therapy. In some embodiments such methods comprise:

- a) administering to the mammal a therapeutically effective amount of at least one first compound that upregulates the Nrf2 pathway, and
- b) administering a therapeutically effective amount of at least one second compound that does not upregulate the Nrf2 pathway.

[0066] In some of embodiments of method 5, the at least one first compound, used in step (a), is a compound of Formula I, II, III, or IV, e.g., DMF or MMF; and the at least one second compound, which is used in step (b), is an immunosuppressive or an immunomodulatory compound that does not upregulate the Nrf2 pathway (e.g., by more than 30%, 50%, 100% over a control).

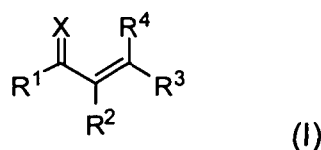
[0067] In some embodiments of method 5, the method comprises administering to the mammal a therapeutically effective amount of a compound of Formula I, II, III, or IV.

[0068] In method 5, the at least one first compound and the at least one second compound may be administered concurrently (as separate compositions or a mixed composition) or consecutively over overlapping or non-overlapping intervals. In the sequential administration, the at least one first compound and the at least one second compound can be administered in any order. In some embodiments, the length of an overlapping interval is more than 2, 4, 6, 12, 24, or 48 weeks, for example.

[0069] Michael addition acceptors generally include olefins or acetylenes conjugated to an electron withdrawing group, such as carbonyl containing groups, thiocarbonyl containing groups, cyano, sulfonyl, sulfonamido, amido, formyl, keto, and nitro. Exemplary carbonyl groups include carboxylic acid esters and carboxylic acid.

[0070] In some embodiments of methods 1-5, the at least one compound being screened, identified, evaluated, or used for treating a neurological disorder is selected from a mild alkylating agent, a Michael addition acceptor, and a compound that is metabolized to a Michael addition acceptor.

[0071] In some embodiments, the Michael addition acceptor has the structure of Formula I:



or a pharmaceutically acceptable salt thereof, wherein:

X is O; S; C(R)(C₁₋₁₂)alkyl; or C(R)(C₂₋₁₂)alkenyl, wherein R is H, (C₁₋₁₂)alkyl or (C₂₋₁₂)alkenyl;

R¹, R², R³ and R⁴ are independently selected from: H; OH; O⁻; CO₂H, CO₂⁻; SH; S⁻; SO₂H, SO₂⁻; (C₁₋₂₄)alkyl; (C₁₋₂₄)alkenyl; (C₆₋₅₀)aryl, CO₂(C₁₋₂₄)alkyl; SO₂(C₁₋₂₄)alkyl; CO₂(C₁₋₂₄)alkenyl; SO₂(C₁₋₂₄)alkenyl; CO₂Y, wherein Y is psoralen-9-yl, retinyl, alpha-tocopherol, calciferyl, corticostreoid-21-yl or monosaccharid-ω-yl; (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; (C₆₋₅₀)aryloxy; (C₁₋₂₄)alkylthio; (C₁₋₂₄)alkenylthio; (C₆₋₅₀)arylthio, amino; amido; arylalkyl; cyano; nitro; sulfonyl; sulfoxido; sulfonamido; formyl; keto; and D and L natural or unnatural amino acids; or any two of X, R¹, R² and R³, and R⁴ may be joined together to form a cyclic moiety; and wherein the alkyl, alkoxy, alkenyl, alkenyloxy, aryl and aryloxy groups may be optionally substituted with at least one group chosen from halogen (F, Cl, Br, or I), OH, (C₁₋₄)alkoxy, nitro and cyano.

[0072] In some embodiments, the at least one Michael addition acceptor has the structure of Formula I, with the following provisos:

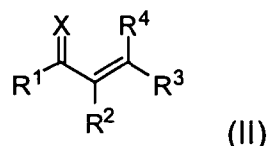
R¹ is selected from: H; OH; O⁻; CO₂H, CO₂⁻; SH; S⁻; SO₂H, SO₂⁻; (C₁₋₂₄)alkyl; (C₁₋₂₄)alkenyl; (C₆₋₅₀)aryl; CO₂(C₁₋₂₄)alkyl; SO₂(C₁₋₂₄)alkyl; CO₂(C₁₋₂₄)alkenyl; SO₂(C₁₋₂₄)alkenyl; CO₂Y, wherein Y is psoralen-9-yl, retinyl, alpha-tocopherol, calciferyl, corticostreoid-21-yl or monosaccharid-ω-yl; (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; (C₆₋₅₀)aryloxy; (C₁₋₂₄)alkylthio; (C₁₋₂₄)alkenylthio; (C₆₋₅₀)arylthio;

arylalkyl; amino; amido; cyano; nitro; sulfonyl, sulfoxido; sulfonamido; formyl, keto; and D or L natural or unnatural amino acids; and wherein the alkyl, alkoxy, alkenyl, alkyenyloxy, aryl and aryloxy groups may be optionally substituted with at least one group chosen from halogen (F, Cl, Br, or I), OH, (C₁₋₄)alkoxy, nitro and cyano;

R² is selected from: H; CO₂H; CO₂⁻; SO₂H; SO₂⁻; (C₁₋₂₄)alkyl; (C₁₋₂₄)alkenyl; (C₆₋₅₀)aryl; CO₂(C₁₋₂₄)alkyl; SO₂(C₁₋₂₄)alkyl; CO₂(C₁₋₂₄)alkenyl; SO₂(C₁₋₂₄)alkenyl; CO₂Y, wherein Y is psoralen-9-yl, retinyl, alpha-tocopherol, calciferyl, corticostreoid-21-yl or monosaccharid-ω-yl; (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; (C₆₋₅₀)aryloxy; (C₁₋₂₄)alkylthio; (C₁₋₂₄)alkenylthio; (C₆₋₅₀)arylthio, amido; arylalkyl; cyano; nitro; sulfonyl, sulfoxido, sulfonamido; formyl, keto; and D or L natural or unnatural amino acids; wherein the alkyl, alkoxy, alkenyl, alkyenyloxy, aryl and aryloxy groups may be optionally substituted with at least one group chosen from halogen (F, Cl, Br, or I), OH, (C₁₋₄)alkoxy, nitro and cyano; and

R³ and R⁴ are independently selected from: H; CO₂H; CO₂⁻; SO₂H; SO₂⁻; (C₁₋₂₄)alkyl; (C₁₋₂₄)alkenyl; (C₆₋₅₀)aryl; CO₂(C₁₋₂₄)alkyl; SO₂(C₁₋₂₄)alkyl; CO₂(C₁₋₂₄)alkenyl; SO₂(C₁₋₂₄)alkenyl; CO₂Y, wherein Y is psoralen-9-yl, retinyl, alpha-tocopherol, calciferyl, corticostreoid-21-yl or monosaccharid-ω-yl; (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; (C₆₋₅₀)aryloxy; (C₁₋₂₄)alkylthio; (C₁₋₂₄)alkenylthio; (C₆₋₅₀)arylthio; amido; arylalkyl; cyano; nitro; cyano; nitro; sulfonyl; sulfoxido; sulfonamido; formyl; and keto; wherein the alkyl, alkoxy, alkenyl, alkyenyloxy, aryl and aryloxy groups may be optionally substituted with at least one group chosen from halogen (F, Cl, Br, or I), OH, (C₁₋₄)alkoxy, nitro and cyano.

[0073] In some embodiments, the at least one Michael addition acceptor has the structure of Formula II:



or a pharmaceutically acceptable salt thereof, wherein:

X is selected from O; S; C(R)(C₁₋₁₂)alkyl; and C(R)(C₂₋₁₂)alkenyl, wherein R is selected from H; (C₁₋₁₂)alkyl; and (C₂₋₁₂)alkenyl; and R¹, R², R³, and R⁴

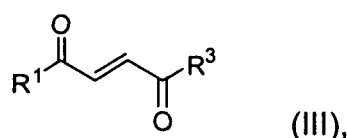
are independently selected from: H; OH; O⁻; CO₂H; CO₂⁻; (C₁₋₁₂)alkyl; (C₁₋₁₂)alkenyl; and CO₂(C₁₋₁₂)alkyl;

or any two of X, R¹, R² and R³ may be joined together to form a cyclic moiety.

[0074] In some embodiments of the compounds of Formulae I-IV, the pharmaceutically acceptable salt is a salt of a metal (M) cation, wherein M can be an alkali, alkaline earth, or transition metal such as Li, Na, K, Ca, Zn, Sr, Mg, Fe, or Mn.

[0075] In some embodiments of methods 1-5, the compounds of Formula I include fumaric acid, its salts, and fumaric acid derivatives.

[0076] In some embodiments, the at least one compound of Formula I has the structure of Formula III:

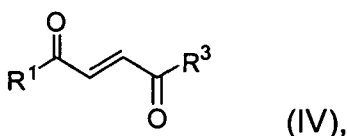


or a pharmaceutically acceptable salt thereof, wherein:

R¹ and R³ are independently selected from OH; O⁻; (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; (C₆₋₅₀)aryloxy; psoralen-9-yloxy; retinyloxy; alpha-tocopheroxy; calciferyloxy; corticostreoid-21-yloxy; monosaccharid- ω -yloxy; amino; and a D or L natural or unnatural amino acid; and wherein at least one of the the (C₁₋₂₄)alkoxy; (C₁₋₂₄)alkenyloxy; and (C₆₋₅₀)aryloxy groups may be optionally substituted with at least one group chosen from halogen (F, Cl, Br, or I), OH, (C₁₋₄)alkoxy, nitro and cyano.

[0077] Compounds wherein at least one of R¹ and R³ is derived from a natural or unnatural D or L amino acid are described in U.S. Application Serial Nos. 10/433,295, paragraphs 10 to 11 and 18-28, and 11/421,083, which are incorporated herein by reference.

[0078] In some embodiments, the compound of formula (I) has the structure of Formula IV:



or a pharmaceutically acceptable salt thereof, wherein:

R¹ and R³ are independently selected from OH; O⁻; (C₁₋₂₄)alkoxy; allyloxy; vinyloxy; (C₆₋₅₀)aryloxy; psoralen-9-yloxy; retinyloxy; alpha-tocopheroxy; calciferyloxy; corticostreoid-21-yloxy; monosaccharid- ω -yloxy; amino; and a D or L natural or unnatural amino acid; and wherein at least one of the the (C₁₋₂₄)alkoxy, allyloxy, vinyloxy, and (C₆₋₅₀)aryloxy may be optionally substituted with at least one group chosen from Cl, F, I, Br, OH, (C₁₋₄)alkoxy, nitro, and cyano.

[0079] In some embodiments, the "fumaric acid derivative" is chosen from the compounds of Formula III, compounds of Formula IV and the following:

1) fumaric acid amides derived from natural and unnatural amino D or L acids, as described in U.S. Patent Application Serial Nos. 10/433,295, paragraphs 10 to 11 and 18-28, and 11/421,083.

2) a carbocyclic or oxacyclic fumaric acid oligomer as described in U.S. Patent Application Serial No. 10/511,564, paragraphs 15-44; and

3) a glycerol or alkane diol or polyol derivative of fumaric acid as described in U.S. Patents Nos. 4,851,439, 5,149,695, 5,451,667, at cols. 2-4.

[0080] In some embodiments, "fumaric acid derivative" is one or more dialkyl fumarates (e.g., DMF), mono alkyl fumarates (MMF) or salts thereof.

[0081] In some of the embodiments of methods 1-5, the at least one compound being screened, evaluated, compared or used for treating a neurological disorder is not fumaric acid or its salt, or a fumaric acid derivative (e.g., DMF or MMF).

[0082] Nrf2 (Nuclear Factor-E2-related factor 2; for sequence of the Nrf2, see Accession No. AAB32188) is a transcription factor that, upon activation by oxidative stress, binds to the antioxidant response element (ARE), and activates transcription of Nrf2-regulated genes. This pathway has been well characterized for its role in hepatic detoxification and chemoprevention through the activation of phase II gene expression. ARE-regulated genes may also contribute to the maintenance of redox homeostasis by serving as endogenous anti-oxidant systems. At present, the list of Nrf2-regulated genes contains over 200 genes encoding proteins and enzymes involved in detoxification and antioxidant response (Kwak et al., J. Biol. Chem., 2003, 278:8135) such as, e.g., HO-1, ferritin, glutathione peroxidase,

glutathione-S-transferases (GSTs), NAD(P)H:quinone oxidoreductases, now commonly known as nicotinamide quinone oxidoreductase 1 (NQO1; EC 1.6.99.2; also known as DT diaphorase and menadione reductase), NQO2, g-glutamylcysteine synthase (g-GCS), glucuronosyltransferase, ferritin, and heme oxygenase-1 (HO-1), as well as any one of the enzymes proteins listed in Table 1 in Chen & Kunsch, *Curr. Pharm. Designs*, 2004, 10:879-891; Lee et al., *J. Biol. Chem.*, 2003, 278(14):12029-38, and Kwak, *supra*.

[0083] Accordingly, in some embodiments, the at least one Nrf2-regulated gene which is used to assess the activation of the Nrf2 pathway is selected from a phase II detoxification enzyme, an anti-oxidant enzyme, an enzyme of the NADPH generating system, and Nrf2 itself. Examples of the phase II detoxification enzymes include NQO1, NQO2, GST-Ya, GST-pi, GST-theta 2, GST-mu (1,2,3), microsomal GST 3, catalytic y-GCS, regulatory-GCS, microsomal epoxide hydrolase, UDP-glucuronosyltransferase, transaldolase, transketolase, and drug-metabolizing enzyme. Examples of the anti-oxidant enzymes include HO-1, ferritin (L), glutathione reductase, glutathione peroxidase, metallothionein I, thioredoxin, thioredoxin reductase, peroxiredoxin MSP23, Cu/Zn superoxide dismutase, and catalase. Examples of the enzymes of the NADPH generating system include malic enzyme, UDP-glucose dehydrogenase, malate oxidoreductase, and glucose-6-phosphate dehydrogenase.

[0084] The antioxidant response element (ARE, also referred to as the electrophile response element (EpRE), GRE1, ARE4, and StREb) is a *cis*-acting DNA regulatory element with a core nucleotide sequence of 5'-TGA(C/T/G)NNNGC-3' (SEQ ID NO:1) (Rushmore et al., *J. Biol. Chem.*, 1991, 266(18):11632-9; see also Nioi et al., *Mutation Res.*, 2004, 555:14-171).

[0085] Accordingly, in some embodiments, the DNA sequence of the ARE element, to which Nrf2 binds (whether the former is a part of an endogenous gene or an artificial construct), comprises the core ARE sequence TGA(C/T/G)NNNGC (SEQ ID NO:2) or the ARE consensus sequence (G/A)TGA(C/T/G)NNNGC(A/G) (SEQ ID

NO:3). In further specific embodiments, the ARE sequence comprises any one of the “minimal enhancer” sequences shown in Table 1.

[0086] In some embodiments, the ARE sequence further comprises at least one of corresponding 5'- and 3'-USR sequences as shown in Table 1. In some embodiments, the ARE sequence comprises the sequence GTGANNNGCA (SEQ ID NO:4), or more particularly, the mouse (NNNN=gtcg) or human (NNNN=ctca) versions thereof.

Table 1

Species	Gene	Element	5'-USR	Minimal enhancer	3'-USR	SEQ ID NO
mouse	nqo1	ARE	agTCaCa	GTGAgtcgGCA	aaat ^{tt}	SEQ ID NO:5
rat	NQO1	ARE	agTCaCa	GTGACTtgGCA	aaat ^{ct}	SEQ ID NO:6
human	NQO1	ARE	agTCaCa	GTGACTcaGCA	gaat ^{ct}	SEQ ID NO:7
mouse	gsta1	EpRE	gcTAA ^t g	GTGACaaaGCA	act ^{ttc}	SEQ ID NO:8
rat	GSTA2	ARE	gcTAA ^t g	GTGACaaaGCA	act ^{ttc}	SEQ ID NO:9
mouse	gsta3	ARE	ctcAgg ^c	ATGACattGCA	ttt ^{ttc}	SEQ ID NO:10
rat	GSTP1	GPE1	agTCAct	ATGATtcaGCA	acaaaa	SEQ ID NO:11
human	GCLC	ARE4	ccTCccc	GTGACTcaGCG	ctt ^{tgt}	SEQ ID NO:12
human	GCLM	EpRE	gaagAca	ATGACTaaGCA	gaaat ^c	SEQ ID NO:13
mouse	ho1	StREb	cccAAcc	ATGACacaGCA	taaa ^{ag}	SEQ ID NO:14
ARE 'core'...			TGACnnnGC			SEQ ID NO:15
ARE consensus ...			<u>TAA</u> nn	<u>ATGAC</u> nnn <u>GCA</u>	<u>aaaa</u>	SEQ ID NO:16
			C	G T G	tttt	

[0087] A current model of Nrf2 function is as follows. Under basal conditions, Nrf2 is sequestered in the cytoplasm to the actin-bound Kelch-like ECH-associated

protein 1 (Keap1; Accession No. NP_987096 for human Keap1), a Cullin3 ubiquitin ligase adaptor protein. More specifically, the N-terminal domain of Nrf2, known as Neh2 domain, is thought to interact with the C-terminal Kelch-like domain of Keap1. In response to xenobiotics or oxidative stress, Nrf2 is released from the Keap1/Nrf2 complex, thereby promoting nuclear translocation of Nrf2 and concomitant activation of ARE-mediated gene transcription. Keap1 function, in turn, requires association with Cullin3, a scaffold protein that positions Keap1 and its substrate in proximity to the E3 ligase Rbx1, allowing the substrate (Nrf2) to be polyubiquitinated and thus targeted for degradation. The exact mechanism of how the Keap1/Nrf2 complex senses oxidative stress is not fully understood. Human Keap1 contains 25 cysteine residues that were hypothesized to function as sensors of oxidative stress; 9 of the cysteines are thought to be highly reactive (Dinkova-Kostova et al., PNAS, 2005, 102(12):4584-9). It was theorized but is not relied on for the purposes of this invention that alkylation of cysteines leads to a conformational change, resulting in the liberation of Nrf2 from Nrf2/Keap1/Cullin3 complexes, followed by nuclear translocation of the liberated Nrf2.

[0088] In some embodiments, methods 1-3 described herein comprise contacting a cell with at least one test compound and determining whether the Nrf2 pathway is upregulated in the cell. In such methods, an upregulation of the Nrf2 pathway above a threshold (e.g., by at least 30%, 50%, 100%, 200%, 500% over a control) indicates that the at least one compound has certain biological properties beneficial in treating a neurological disease (e.g., neuroprotective properties).

[0089] The ability of a compound to activate the Nrf2 pathway can be determined by one or more in vitro and in vivo assays, including, e.g., the following assays described below.

[0090] i) *Expression levels of Nrf2*--The sequence of the promoter region of the *nrf2* gene (-1065 to -35) has been published, for example, in Chan et al., PNAS, 1996, 93:13943-13948. One may use an artificially constructed expression construct containing the Nrf2 promoter element and an artificial reporter gene. Alternatively, one may use PCR or Northern blotting to determine expression levels of Nrf2 mRNA, or Western blotting to determine Nrf2 protein levels. Exemplary procedures for

determining expression levels of Nrf2 are described in Kwak et al., Mol. Cell. Biol. 2002, 22(9):2883-2892 and Kwak et al., Mol. Med., 2001, 7:135-145. Antibodies against Nrf2 are can be produced by methods known in the art and are commercially available from, for example, StressGen. Accordingly, in some embodiments, the Nrf2 pathway is activated so that the expression levels of Nrf2 are increased by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0091] ii) *Subcellular localization and/or nuclear translocation of Nrf2*-- Such assays include cell staining, or analysis of cytoplasmic versus nuclear cell extracts. For example, a Nrf2-green fluorescence protein (GFP) fusion protein construct can be made and introduced into cells and visualized as described in, e.g., Kraft et al., J. Neurosci., 2004, 24, 1101-1112; and Satoh et al., PNAS, 2006, 103(3):768-773. Accordingly, in some embodiments, the Nrf2 pathway is activated so that the ratio between cytomplasmic and nuclear Nrf2 is elevated by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0092] iii) *Expression levels and/or activity of one or more genes under the control of Nrf2*--Such genes under the control of Nrf2 include endogenous or artificially introduced reporter genes in reporter constructs introduced into cells. For example, expression levels of endogenous or exogenously introduced NQO1 may be determined as described in the Examples. Alternatively, a reporter gene construct with one or more ARE sites operably linked to a reporter gene (e.g., luciferase or GFP) can be made, as described in, e.g., Satoh et al., PNAS, 2006, 103(3):768-773. Expression levels of an Nrf-2 induced gene product can be measured at the protein (e.g., by Western blotting or enzymatic activity assays) or at the mRNA levels (e.g., by PCR). Methods for performing RT-PCT are described in, e.g., Calabrese et al., J. Neurosci. Res., 2005, 79:509-521 for HO-1, in Wierinckx et al., J. Neuroimmunology, 2005, 166:132-143 for NQO1. Methods for measuring enzymatic activity of NQO1, using for example, menadione as a substrate, are described in Dinkova-Kostova et al., PNAS, 2001, 98:3404-09 or by Prochaska et al., Anal. Biochem., 1988, 169:328-336. Methods for measuring GST activity, using for example, 1-chloro-2,4-dinitrobenzene as

a substrate, are described in Ramos-Gomez et al., J. Neurosci., 2004, 24(5):1101-1112 and Habig et al., 1974, J. Biol. Chem., 219, 7130-7139. Methods for measuring HO-1 activity are described in, e.g., in Calabrese et al., 2005, J. Neurosci. Res., 79:509-521. Accordingly, in some embodiments, the Nrf2 pathway is activated so that the expression levels and/or activity of the gene produced are increased by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0093] iv) *Levels of Nrf2 binding to ARE*--For example, such assays may utilize electromobility shift assays (EMSA) and Chromatin Immunoprecipitation (ChIP) assay, as described in, e.g., Satoh et al., PNAS, 2006, 103(3):768-773 and Kwak et al., Mol. Cell Biol., 2002, 22(9):2883-2892. Accordingly, in some embodiments, the Nrf2 pathway is activated so that the level of Nrf2 binding to ARE is increased by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0094] v) *The stability of Nrf2/Keap1 complexes*--Such assay may include analysis of immunoprecipitated complexes with Nrf2 and/or Keap1 or other Nrf2/Keap1-associated proteins as described in, e.g., Satoh et al., PNAS, 2006, 103(3):768-773. Anti-Keap1 antibodies can be produced using methods known in the art and are available commercially from, for example, Santa Cruz Biotechnology. Accordingly, in some embodiments, the Nrf-2 pathway is activated so that the stability of Nrf2/Keap1 complexes is increased by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0095] vi) *Modification (e.g., alkylation levels) of Keap1 and other Nrf2/Keap1-associated proteins*--Such assays may include mass spectrometric analysis of immunoprecipitated Keap1, using techniques as described in, e.g., Dinkova-Kostova et al., PNAS, 2005, 102(12):4584-9 and Gao et al., J. Biol. Chem., on-line pub. Manuscript M607622200. In some embodiments, the Nrf-2 pathway is activated so that the level of Keap1 and other Nrf2/Keap1-associated proteins is increased by, for example, at least 30%, 50%, 100%, 200%, 500% or more as compared to the non-activated state.

[0096] Alkylating capacity of a compound can be assessed using recombinant Keap1, by a competition reaction with 5,5'-dithiobis(2-nitrobenzoic acid) (DTNB) as described in, e.g., Gao et al., J. Biol. Chem., on-line pub. Manuscript M607622200.

[0100] In some embodiments, the cell being contacted with at least one test compound is a neuron or a neuronal cell line. In some embodiments, the cell being contacted with the at least one test compound is selected from a colon carcinoma cell line (e.g., DLD1), a neuroblastoma cell line (e.g., SkNSH or IMR32), and a primary monocyte. The cell may be a cell in culture (in vitro) or be inside of an animal (in vivo).

[0101] Cell viability, and in particular, neuronal viability can be assessed in vivo or in vitro using any suitable method, including methods as described in the Examples. For example, neuronal viability can be assessed using an MTT assay after exposure of neuronal cell cultures to cytotoxic levels of glutamate as described in, e.g., Shih et al., J. Neurosci., 2005, 25(44):10321-35. Additionally, cell viability may also be assessed in assays in which cell death is induced by oxidative damage, for example, by the addition of glucose oxidase to astrocyte cell cultures, as described in, e.g., Calabrese et al., J. Neurosci. Res., 2005, 79:509-521. In vivo assays may be performed as described in, e.g., Misgeld, Histochem. Cell Biol., 2005, 124:189-196.

[0102] The amount of the reporter gene expressed can be determined by any suitable method. Expression levels, at the RNA or the protein level, can be determined using routine methods. Expression levels are usually scaled and/or normalized per total amount of RNA or protein in the sample and/or a control, which is typically a housekeeping gene such as actin or GAPDH. RNA levels are determined by quantitative PCR (e.g., RT-PCR), Northern blotting, or any other method for determining RNA levels, e.g., as described in Cloning: A Laboratory Manual, by Sambrook et al. (eds.), 2nd ed., Cold Spring Harbor Laboratory Press, 1989; Lodie et al., Tissue Eng., 2002, 8(5):739-751; or as described in the Examples. Protein levels are determined using, Western blotting, ELISA, enzymatic activity assays, or any other method for determining protein levels as described in, e.g., Current Protocols in Molecular Biology, by Ausubel et al. (eds.), John Wiley and Sons, 1998.

[0103] Expression levels may also be determined using reporter gene assays in cell/tissue extracts or by tissue or whole-animal imaging. In addition to MRI, tissue imaging on living animals can be performed by fluorescence detection (Hoffman Lancet Oncol., 2002 3:546-556; Tung et al., Cancer Res., 2000, 60:4953-4958), bioluminescence detection (Shi et al., PNAS, 2001, 98:12754-12759; Luke et al., J. Virol., 2002, 76:12149-12161; and U.S. Patent Nos. 5,650,135 and 6,217,847), positron emission tomography (Liang et al., Mol. Ther., 2002, 6:73-82, near-infrared fluorescence (Tung et al., Cancer Res., 2000, 60:4953-4958), or X-ray imaging (Hemminki et al., J. Nat. Cancer Inst., 2002, 94:741-749).

[0104] A neurological disease in methods 1-5 above can be a neurodegenerative disease such as, for example, ALS, Parkinson's disease, Alzheimer's disease, and Huntington's disease. The neurological disease can also be multiple sclerosis (MS), or other demyelinating diseases of the central or peripheral nervous system. In some embodiments the form of MS in methods 1-5 is selected from: relapsing remitting MS (RRMS), secondary progressive MS (SPMS), primary progressive MS (PPMS), and malignant MS (Marburg Variant).

[0105] The subject being treated or administered the compound as per methods described herein, is a mammal in need thereof, such as a subject in need of neuroprotection, including a subject who has or is at risk for developing a demyelinating and another specified neurodegenerative disease. The subject is mammalian, and can be a rodent or another laboratory animal, e.g., a non-human primate. In some embodiments, the subject is human.

[0106] Neurodegenerative diseases are described in, for example, Neurodegenerative Diseases: Neurobiology, Pathogenesis and Therapeutics, M. Flint Beal, Anthony E. Lang, Albert C. Ludolph, Cambridge University Press (July 11, 2005). Examples of neurological diseases suitable for the methods described herein include neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS), Parkinson's disease, Alzheimer's disease, and Huntington's disease. Other examples include demyelinating neurological disease including, in addition to MS, the following diseases: acute haemorrhagic leucoencephalomyelitis, Hurst's disease, acute

disseminated encephalomyelitis, optic neuritis, Devic's disease, spinal cord lesions, acute necrotizing myelitis, transverse myelitis, chronic progressive myelopathy, progressive multifocal leukoencephalopathy (PML), radiation myelopathy, HTLV-1 associated myelopathy, monophasic isolated demyelination, central pontine myelinolysis, and leucodystrophy (e.g., adrenoleucodystrophy, metachromatic leucodystrophy, Krabbe's disease, Canavan's disease, Alexander's disease, Pelizaeus-Merzbacher disease, vanishing white matter disease, oculodentodigital syndrome, Zellweger's syndrome), chronic inflammatory demyelinating polyneuropathy (CIPD), acute inflammatory demyelinating polyneuropathy (AIPD), Leber's optic atrophy, and Charcot-Marie-Tooth disease.

[0107] Additional examples of diseases suitable for the methods described herein include polyneuritis and mitochondrial disorders with demyelination. These disorders may be co-presented with, and possibly aggravated by diabetes, e.g., insulin-dependent diabetes mellitus (IDDM; type I diabetes), or other diseases.

[0108] A test compound may be further assayed in an animal model of MS, known as Experimental Autoimmune Encephalomyelitis (EAE) (Tuohy et al., *J. Immunol.*, 1988, 141:1126-1130, Sobel et al. *J. Immunol.*, 1984, 132:2393-2401, and Traugott, *Cell Immunol.*, 1989 119:114-129). Chronic relapsing EAE provides a well established experimental model for testing agents that would be useful for the treatment of MS. The mouse EAE is an induced autoimmune demyelinating disease with many similarities to human MS in its clinical manifestations. In both EAE and MS, clinical disease is associated with blood-brain barrier (BBB) dysfunction, infiltration of central nervous system by mononuclear cells (mainly macrophages and T lymphocytes, and serum products), and demyelination (Baker et al. *J. Neuroimmunol.*, 1990, 28:261; Butter et al., *J. Neurol. Sci.*, 1991, 104:9; Harris et al., *Ann. Neurol.*, 1991, 29:548; Kermonde et al., *Brain*, 1990, 113:1477).

[0109] Clinical signs of MS and demyelinating pathology in EAE result from immunization with CNS myelin proteins or peptides (e.g., MBP, PLP, and MOG) under Th1 conditions (direct immunization model), or by adoptive transfer of CNS antigen-specific Th1 cells (adoptive transfer model) (Ben-Nun et al., *Eur. J. Immunol.*,

1981, 11:195-199; Ando et al., *Cell Immunol.*, 1989, 124:132-143; Zamvil et al., *Nature*, 1985, 317:355-358; Zamvil et al., *Ann. Rev. Immunol.*, 1990, 8:579-621). For example, in the SJL mouse model of EAE, immunization with the CNS peptide PLP 139-151 or adoptive transfer of PLP-specific Th1 cells results in a disease course consisting of an acute phase with loss of tail tone on day 10 to day 12, followed by hind limb paralysis and CNS mononuclear cell infiltration (Tuohy et al., *J. Immunol.*, 1988, 141:1126-1130, Sobel et al., *J. Immunol.*, 1984, 132:2393-2401, and Traugott, *Cell Immunol.*, 1989, 119:114-129). Resolution of clinical signs and recovery occurs on day 20 to day 25 and the animals may undergo several more relapses less severe than the initial phase. EAE has been used to evaluate new therapeutic approaches to T-cell-mediated autoimmune disease because of the clinical and histopathological similarities to the human demyelinating MS.

[0110] The ability of a compound to slow or prevent neurodegeneration (including demyelination and neuronal death) can be assessed in the EAE model or another animal model, including for example, Thieler's murine encephalomyelitis virus (TMEV)-induced demyelinating disease, murine hepatitis virus (MHV), Semliki Forest Virus, or Sindbis virus as described in, e.g., Ercoli et al., *J. Immunol.*, 2006, 175:3293-3298.

[0111] A compound may be optionally tested in at least one additional animal model (see, generally, *Immunologic Defects in Laboratory Animals*, eds. Gershwin et al., Plenum Press, 1981), for example, such as the following: the SWR X NZB (SNF1) mouse model (Uner et al., *J. Autoimmune Disease*, 1998, 11(3):233-240), the KRN transgenic mouse (K/BxN) model (Ji et al., *Immunol. Rev.*, 1999, 69:139); NZB X NZW (B/W) mice, a model for SLE (Riemekasten et al., *Arthritis Rheum.*, 2001, 44(10):2435-2445); the NOD mouse model of diabetes (Baxter et al., *Autoimmunity*, 1991, 9(1):61-67), etc.); or mouse models of multiple sclerosis (see, e.g., Linker et al., *Eur. J. Immunol.*, 2002, 8(6):620-624, and Eugster et al., *Nat. Med.*, 1999, 29:626-632; and Gold et al., *Brain*, 2006, 129:1953-1971).

[0112] Preliminary doses, for example, as determined in animal tests, and the scaling of dosages for human administration is performed according to art-accepted

practices. Toxicity and therapeutic efficacy can be determined by standard pharmaceutical procedures in cell cultures or experimental animals, e.g., for determining the LD₅₀ (the dose lethal to 50% of the population) and the ED₅₀ (the dose therapeutically effective in 50% of the population). The dose ratio between toxic and therapeutic effects is the therapeutic index and it can be expressed as the ratio LD₅₀/ED₅₀. In some embodiments compositions that exhibit large therapeutic indices are used.

[0113] The therapeutically effective dose can be estimated initially from cell culture assays. A dose may be formulated in animal models to achieve a circulating plasma concentration range that includes the IC₅₀ (i.e., the concentration of the therapeutic compound which achieves a half-maximal inhibition of symptoms) as determined in cell culture assays or animal models. Levels in plasma may be measured, for example, by ELISA or HPLC. The effects of any particular dosage can be monitored by a suitable bioassay. Examples of dosages are: about 0.1 x IC₅₀, about 0.5 x IC₅₀, about 1 x IC₅₀, about 5 x IC₅₀, 10 x IC₅₀, about 50 x IC₅₀, and about 100 x IC₅₀.

[0114] The data obtained from the in vitro assays or animal studies can be used in formulating a range of dosages for use in humans. Therapeutically effective dosages achieved in one animal model can be converted for use in another animal, including humans, using conversion factors known in the art (see, e.g., Freireich et al., *Cancer Chemother. Reports*, 1966, 50(4):219-244 and Table 2 for Equivalent Surface Area Dosage Factors).

Table 2

To: From:	Mouse (20 g)	Rat (150 g)	Monkey (3.5 kg)	Dog (8 kg)	Human (60 kg)
Mouse	1	1/2	1/4	1/6	1/12
Rat	2	1	1/2	1/4	1/7
Monkey	4	2	1	3/5	1/3
Dog	6	4	3/5	1	1/2
Human	12	7	3	2	1

[0115] In some embodiments the dosage of such compounds lies within a range of circulating concentrations that include the ED₅₀ with little or no toxicity. In some embodiments the dosage varies within this range depending upon the dosage form employed and the route of administration utilized. Generally, a therapeutically effective amount may vary with the subject's age, condition, and sex, as well as the severity of the medical condition in the subject. Examples of pharmaceutically acceptable dosages for compounds described herein are from 1 µg/kg to 25 mg/kg, depending on the compounds, severity of the symptoms and the progression of the disease. The appropriate therapeutically effective doses can be selected by a treating clinician and in some embodiments range approximately from 1 µg/kg to 20 mg/kg, from 1 µg/kg to 10 mg/kg, from 1 µg/kg to 1 mg/kg, from 10 µg/kg to 1 mg/kg, from 10 µg/kg to 100 µg/kg, from 100 µg to 1 mg/kg. Additionally, certain specific dosages are indicated in the Examples.

[0116] For DMF or MMF, an effective amount can range from 1 mg/kg to 50 mg/kg (e.g., from 2.5 mg/kg to 20 mg/kg or from 2.5 mg/kg to 15 mg/kg). Effective doses will also vary, as recognized by those skilled in the art, dependent on route of

administration, excipient usage, and the possibility of co-usage with other therapeutic treatments including use of other therapeutic agents. For example, an effective dose of DMF or MMR to be administered to a subject orally can be from about 0.1 g to 1 g per day, 200 mg to about 800 mg per day (e.g., from about 240 mg to about 720 mg per day; or from about 480 mg to about 720 mg per day; or about 720 mg per day). For example, the 720 mg per day may be administered in separate administrations of 2, 3, 4, or 6 equal doses.

[0117] The dosage may be determined by a physician and adjusted, as necessary, to suit observed effects of the treatment. The compositions may be given as a bolus dose, to maximize the circulating levels for the greatest length of time after the dose. Continuous infusion may also be used after the bolus dose.

[0118] In some embodiments, compositions used in the methods described herein further comprise a pharmaceutically acceptable excipient. As used herein, the phrase "pharmaceutically acceptable excipient" refers to any and all solvents, dispersion media, coatings, antibacterial and antifungal agents, isotonic and absorption delaying agents, and the like, that are compatible with pharmaceutical administration. The use of such media and agents for pharmaceutically active substances is well known in the art. The compositions may also contain other active compounds providing supplemental, additional, or enhanced therapeutic functions. The pharmaceutical compositions may also be included in a container, pack, or dispenser together with instructions for administration.

[0119] A pharmaceutical composition is formulated to be compatible with its intended route of administration. Methods to accomplish the administration are known in the art. "Administration" is not limited to any particular delivery system and may include, without limitation, parenteral (including subcutaneous, intravenous, intramedullary, intraarticular, intramuscular, or intraperitoneal injection), rectal, topical, transdermal, or oral (for example, in capsules (e.g., as powder, granules, microtablet, micropellets, etc.), suspensions, or tablets). Examples of some of formulations containing DMF and/or MMF are given in, e.g., US Patents Nos. 6,509,376, and 6,436,992.

[0120] Administration to an individual may occur in a single dose or in repeat administrations, and in any of a variety of physiologically acceptable salt forms, and/or with an acceptable pharmaceutical carrier and/or additive as part of a pharmaceutical composition. Physiologically acceptable salt forms and standard pharmaceutical formulation techniques and excipients are well known to persons skilled in the art.

[0121] The following Examples are intended for illustrative purposes and do not limit the inventions claimed.

EXAMPLES

Example 1

[0122] Human colon carcinoma DLD1 cells were treated with DMF or MMF at indicated concentrations (5, 15, or 50 μ M) for 16 hours, rinsed with PBS, and harvested into reducing SDS sample buffer. The lysates were subjected to SDS PAGE and the separated proteins were electrophoretically transferred onto nitrocellulose membranes for Western blot analysis. To detect Nrf2 and NQO1, the membranes were incubated with the respective primary antibodies overnight at 4°C, washed, and incubated with peroxidase-conjugated secondary antibodies followed by the chemiluminescent peroxidase substrate. Detection of the target protein band luminescence and image acquisition were done using CCD-equipped imaging station Kodak2000R. The results shown in Figure 1, demonstrate that DMF and MMF are potent activators of Nrf2 at concentrations within clinical exposure range.

Example 2

[0123] DLD1 cells were grown in MEM supplemented with 10% fetal bovine serum. The cells were transfected with the indicated siRNA's using the Lipofectamine reagent (Invitrogen) according to the manufacturer's instructions and 30 hrs later stimulated with 30 μ M DMF for 40 hours. The cells were harvested and processed for Western blotting analysis of Nrf2 and NQO1 levels as described in Example 1. Sources and

the identity of reagents used in Examples 1 and 2 are specified Table 3 below:

	Target	Reagent	Source/Sequence	Vendor
Primary Antibody	Nrf2	Nrf2 (T-19)	goat polyclonal antibody	Santa Cruz Biotechnology
	Keap1	Keap1 (E-20)	goat polyclonal antibody	Santa Cruz Biotechnology
	NQO1	NQO1 (A180)	mouse monoclonal antibody	Santa Cruz Biotechnology
	GAPDH	Anti-GAPDH	mouse monoclonal antibody	Ambion
Secondary antibody	anti-mouse	HRP-Mouse IgG	sheep	Amersham Biosciences
	anti-rabbit	HRP-Rabbit IgG	donkey	Amersham Biosciences
	anti-Goat	HRP-Goat IgG	Bovine	Santa Cruz Biotechnology
siRNA	Nrf2	Nrf2-2	UCAUUGAACUGC UCUUUGGUU (antisense) (SEQ ID NO:17)	Dharmacon
	Keap1	Keap1-1	GAAUUAAGGCGG UUUGUCCUU (antisense) (SEQ ID NO:18)	Dharmacon

[0124] The results are shown in Figure 2 (for ease of representation, the image of the Western blot is turned upside down). The results demonstrate that DMF-induced upregulation of NQO1 requires Nrf2 and can be mimicked by activation of

Nrf2 through repression of Keap1. Therefore, DMF acts as an Nrf2 agonist causing cellular accumulation of Nrf2 and Nrf2 target gene expression.

Example 3

[0125] For induction of EAE, mice received s.c. injections in the flanks and tail base of 50 µg MOG 35–55 peptide in PBS emulsified in an equal volume of complete Freund's adjuvant (CFA) containing Mycobacterium tuberculosis H37RA (Difco, Detroit MI, USA) at a final concentration of 0.5 mg/ml. Two injections of pertussis toxin (List Biological Laboratories Inc., California, USA; 200 ng per mouse i.p) were given on days 0 and 2.

[0126] DMF and MMF was diluted in 200 µl 0.08% Methocel/H₂O as vehicle and administered by oral gavage starting from day 3 post immunization (p.i) until termination. Each treatment group consisted of 8 animals: vehicle alone as a negative control, 5 mg/kg body weight DMF twice a day, 15 mg/kg body weight DMF twice a day, 15 mg/kg body weight MMF twice a day. The compounds were obtained via Fumapharm AG. Oral gavage was used to ensure exact dosing and to avoid compound degradation.

[0127] Spinal cord tissues were fixed in 4% paraformaldehyde and embedded in paraffin. Slides were deparaffinized and rehydrated in graded alcohol solutions. Antigen retrieval was performed by immersing the slides in 10 mM Citrate, pH 6.0 for 20 minutes in a pressure cooker at 120 C (Pascal, Dako Cytomation).

[0128] Immunohistochemistry was performed using the Dako autostainer as follows. Endogenous peroxidase was quenched by a 10 minute incubation in 3% H₂O₂ / Methanol. The rabbit anti Nrf2 antibody C-20 (sc-722, Santa Cruz Biotechnology) was added at a 1:250 dilution in Dako Diluent with Background Reducing Components (Dako # S3022) C-20 antibody was detected using the Envision anti rabbit labeled polymer-HRP (Dako #K4003) and DAB (Vector Labs #SK-4100) was used as the chromogenic substrate. Morphometric analysis of Nrf2 immunostaining was performed using ImageJ software from NIH (<http://rsb.info.nih.gov/ij/>).

[0129] The results, shown in Figures 3 and 4, demonstrate MMF and DMF activation of Nrf2 in vivo.

* * *

[0130] All publications and patent documents cited herein are incorporated by reference in their entirety. To the extent the material incorporated by reference contradicts or is inconsistent with the present specification, the present specification will supersede any such material.

CLAIMS

1. A method of evaluating neuroprotective properties of at least one test compound, the method comprising:
 - a) contacting a cell with the at least one test compound,
 - b) determining whether the Nrf2 pathway is upregulated in the cell,
 - c) determining whether the at least one test compound slows or prevents at least one of demyelination, axonal loss, and neuronal death, and
 - d) selecting the test compound as a candidate for treating neurodegeneration in a neurological disease if 1) the Nrf2 pathway is upregulated and, optionally,
 - e) further determining whether at least one of demyelination, axonal loss, and neuronal death are prevented or slowed by the compound.

2. The method of claim 1, wherein the neurological disease is a demyelinating disease.

3. The method of claim 2, wherein the demyelinating disease is multiple sclerosis.

4. The method of claim 1, wherein the cell in step a) is contacted with a plurality of test compounds.

5. The method of claim 1, wherein the Nrf2 pathway upregulation is determined by the levels of expression or activity of NQO1.

6. The method of claim 1, wherein the Nrf2 pathway is upregulated by at least 30% as indicated by one or more of the following parameters:

- i) expression levels of at least one of endogenously produced and exogenously introduced Nrf2;
 - ii) at least one of subcellular localization and nuclear translocation of Nrf2;
 - iii) the expression level of at least one gene under control of Nrf2;
 - iv) the level of Nrf2 binding to the Nrf2-binding DNA element ARE;
 - v) the stability of Nrf2/Keap1 complexes; and
 - vi) modification levels of at least one protein selected from Keap1 and other Nrf2/Keap1-associated proteins.
7. The method of claim 6, wherein the at least one gene under control of Nrf2 is an Nrf2-regulated reporter gene in an artificial reporter construct.
8. The method of claim 1, further comprising comparing the level of Nrf2 pathway upregulation by the at least one test compound with the level of Nrf2 pathway upregulation by at least one comparator compound.
9. The method of claim 8, wherein the at least one comparator compound is selected from dimethyl fumarate and monomethyl fumarate.
10. The method of claim 1, wherein the at least one test compound has the structure of Formula I.
11. The method of claim 1, wherein the at least one test compound is selected from fumaric acid, its salts, and fumaric acid derivatives.
12. The method of claim 1, wherein the at least one test compound is chosen from FTY 720, ABT-874, GSK683699, NeuroVax, MLN 1202, interferon γ , Tysabri™, Rituxan, TV 5010, NBI-788, MBP8298, Cladribine, Teriflunomide, Temsirolimus, and Laquinimod.

13. A method of treating a mammal having a neurological disease, comprising:
- a) selecting a test compound according to the method of any one of claims 1-10, and
 - b) administering the selected test compound a mammal in need thereof, thereby treating neurodegeneration in the mammal.
14. A method of treating a mammal having a neurological disease by combination therapy, the method comprising:
- a) administering to the mammal a therapeutically effective amount of at least one first compound that upregulates the Nrf2 pathway, and
 - b) administering a therapeutically effective amount of at least one second compound that does not upregulate the Nrf2 pathway.
15. The method of claim 14, wherein the at least one first compound is selected from fumaric acid, its salts, and fumaric acid derivatives.
16. The method of claim 13 or 14, wherein the neurological disease is a demyelinating disease.
17. The method of claim 16, wherein the demyelinating disease is multiple sclerosis.

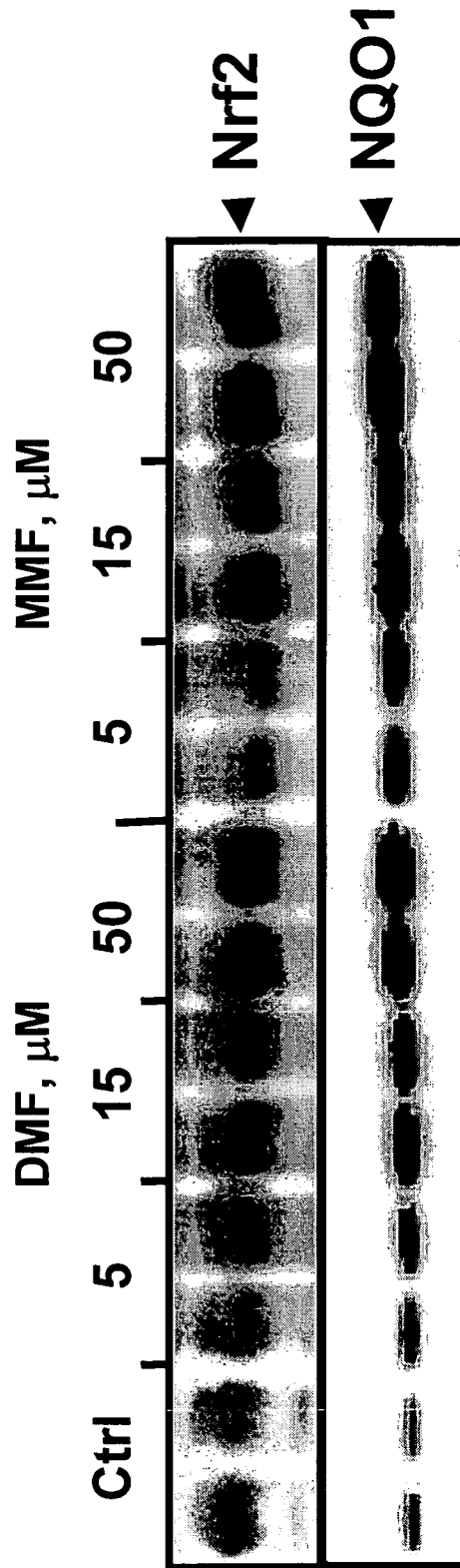


Figure 1

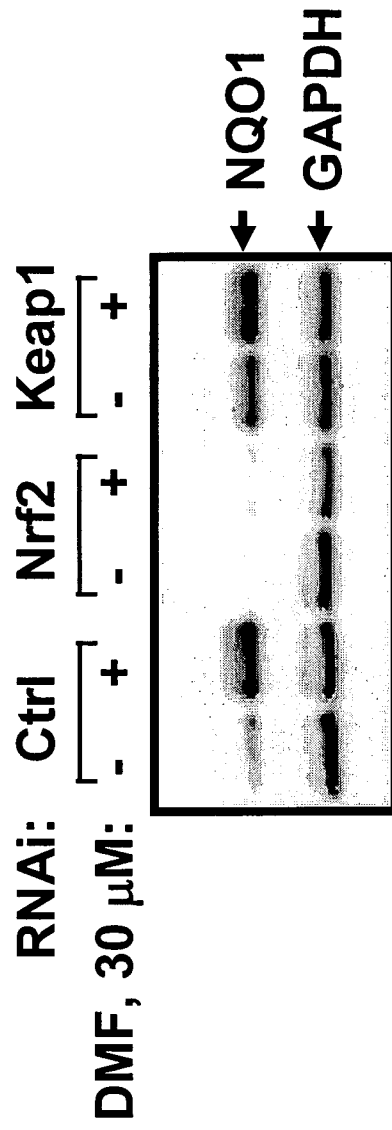


Figure 2

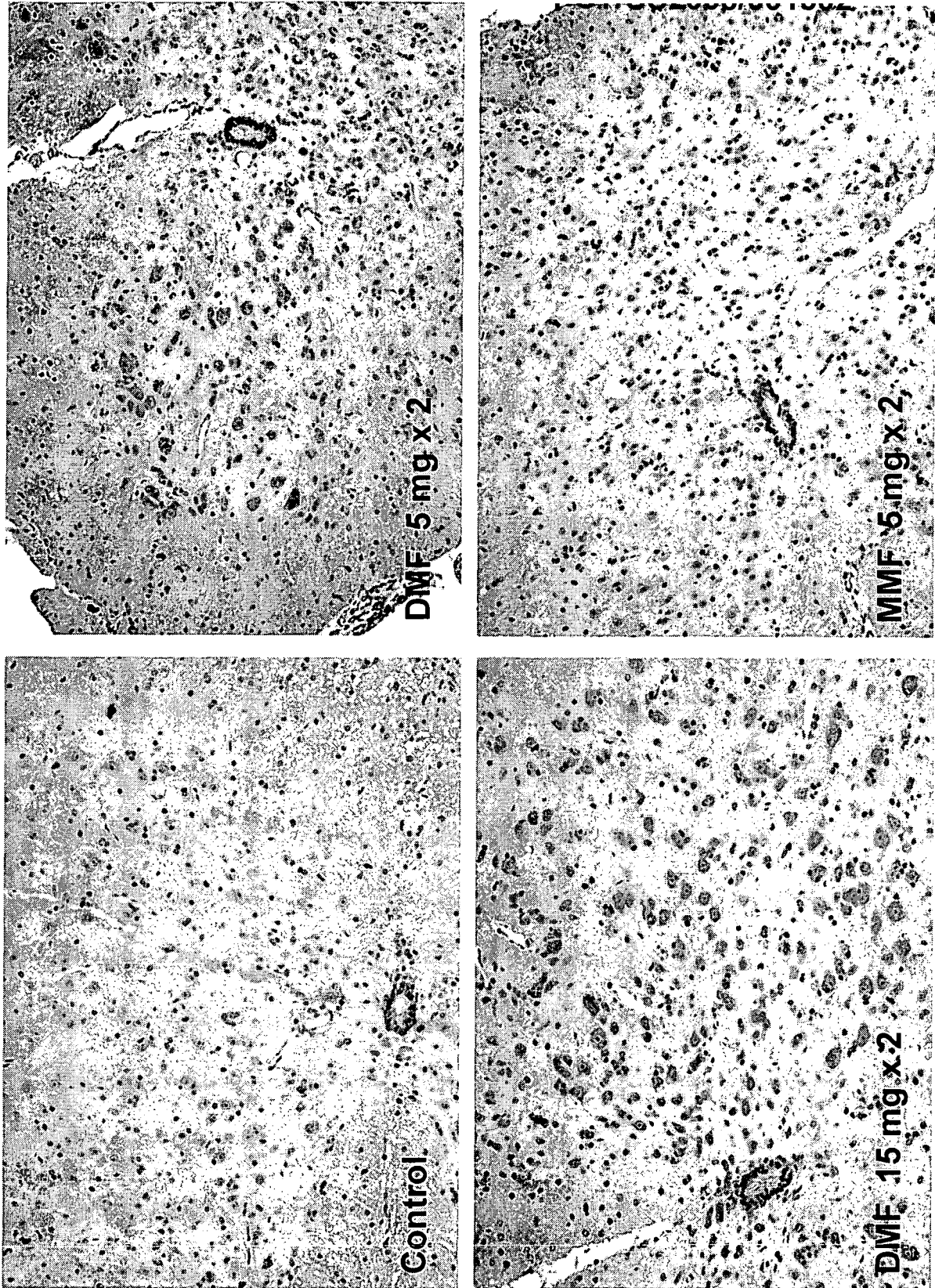


Figure 3

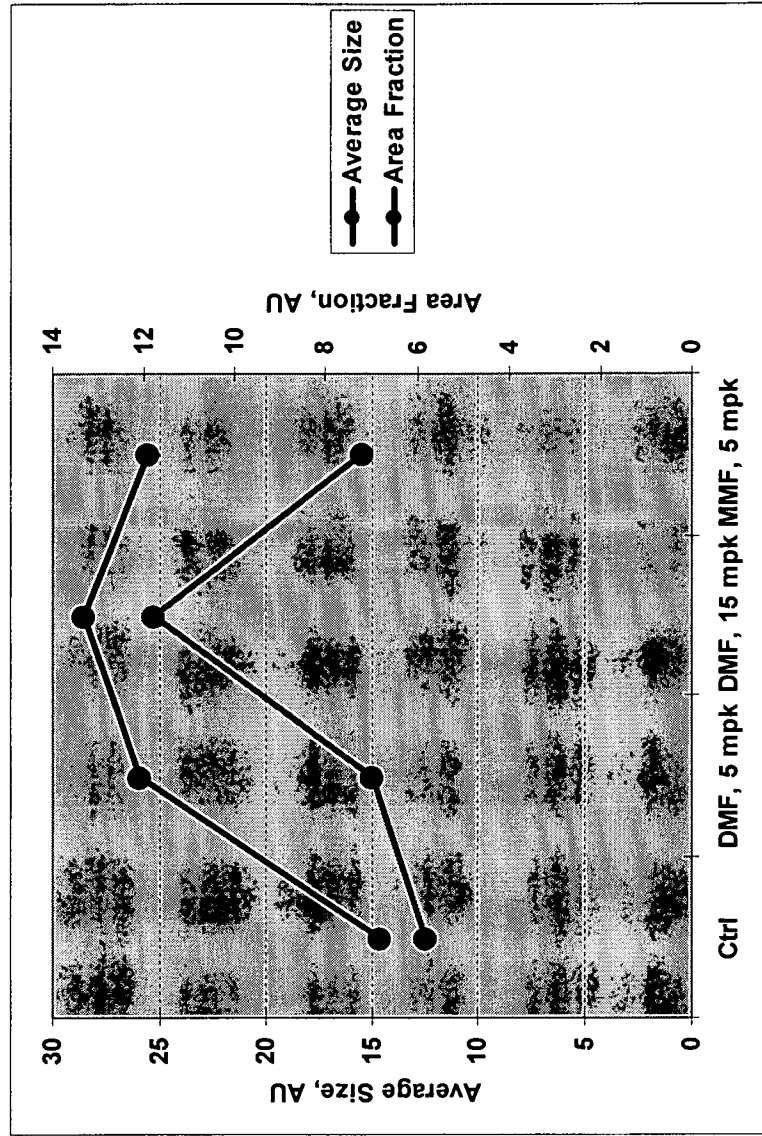


Figure 4