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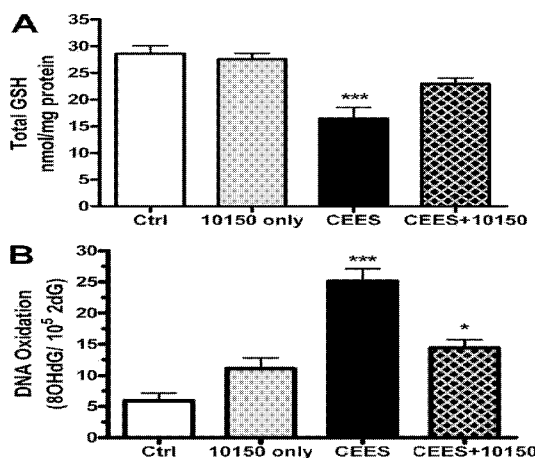


FIGURE 8

(57) Abstract: Compounds may be administered to prevent or rescue organ injury following exposure to alkylating agents, such as sulfur mustards. The compounds may be substituted metalloporphyrins.

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METHODS FOR TREATING INJURY ASSOCIATED WITH EXPOSURE TO AN ALKYLATING SPECIES

CROSS-REFERENCES TO RELATED APPLICATIONS[0001] This application claims priority to and benefit under 35 U.S.C. § 119(e) to U.S. Provisional Application Serial No. 61/055,919, filed May 23, 2008, the disclosure of which is expressly incorporated by reference herein in its entirety.

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] This invention was made, at least in part, with U.S. government support under Grant No. U54 ES015678, awarded by the National Institutes of Health. The U.S. government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] Bis (2-chloroethyl sulfide) or sulfur mustard (SM) was first synthesized in the late 1880s and since has been used as a warfare agent on a number of occasions. SM was first used in World War I and has been used in warfare as recently as the Iran-Iraq conflict of the late 1980s. Although SM is less of a threat in warfare as it once was, it still poses a threat to military and civilian personnel because of current concerns for its deployment in a terrorist attack.

[0004] Sulfur mustards are classic vesicating agents that mainly affect the skin, eyes, and respiratory system. Medical surveillance of individuals exposed to mustard gas in the early 1980's has documented a number of respiratory conditions including bronchiolitis obliterans, asthma, and lung fibrosis that can persist through out the victims' lifetime.

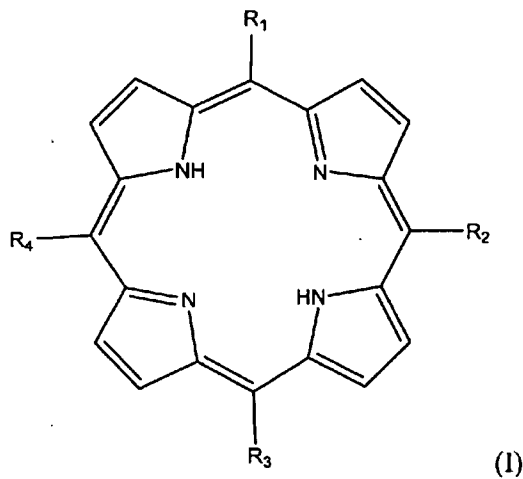
[0005] There is currently no known antidote for SM poisoning. Upon exposure, the best recourse is decontamination and supportive treatment. Decontamination of the skin is relatively straight forward and beneficial, whereas internal exposure such a inhalation of sulfur mustards is much more difficult to treat.

[0006] It can be seen from the foregoing discussion that there is a need for developing agents that are capable of attenuating, preventing, and/or rescuing organ injury from the deleterious effects resulting from exposure to alkylating agents (e.g., inhalation damage), such as sulfur mustards. The invention addresses these and other needs in the art.

BRIEF SUMMARY OF THE INVENTION

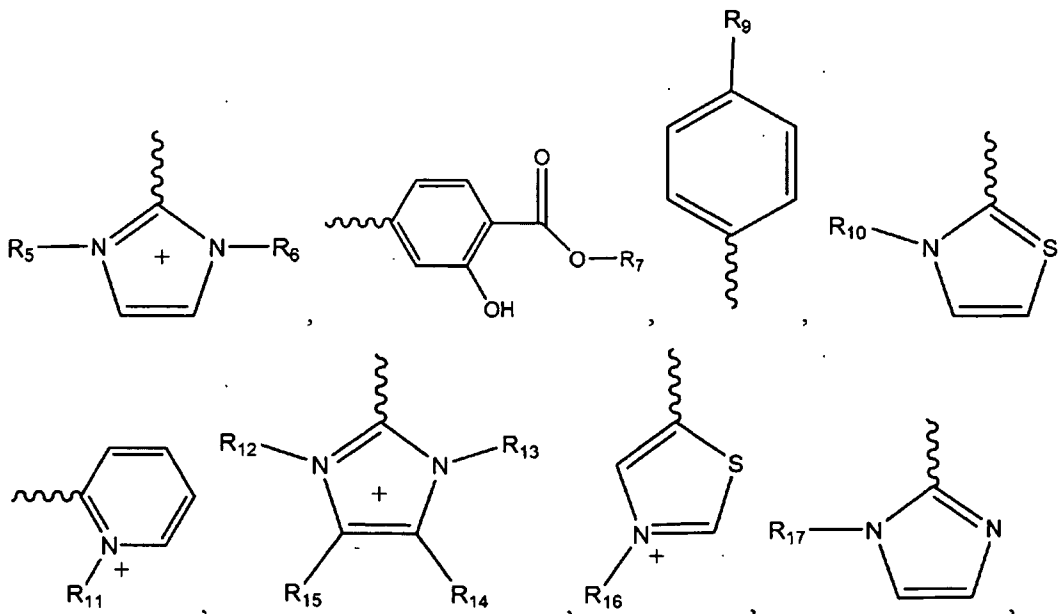
[0007] Provided herein are, *inter alia*, methods for rescuing or preventing organ injury following exposure to alkylating agents by using substituted porphyrins as the active agent or alkylating agent protectant, such as a mimetic of superoxide dismutase and/or catalase. The methodology of the invention may implemented as follows.

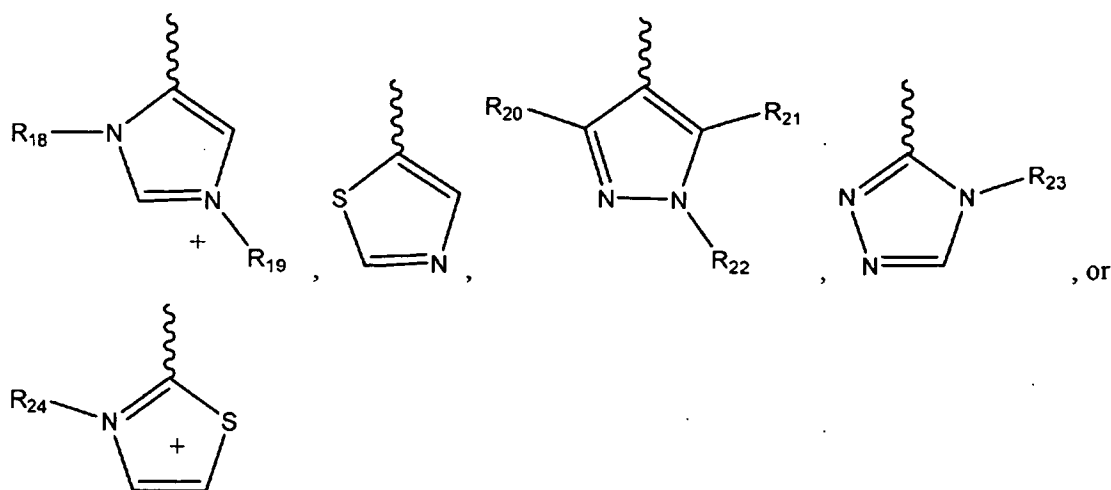
[0008] According to one aspect of the invention, a method of treating an injury associated with exposure to an alkylating agent in a subject includes administering to a subject in need thereof an effective amount of a compound of Formula



10 or a pharmaceutically acceptable salt thereof.

R₁, R₂, R₃, and R₄ may each independently be -H, -CF₃, -CO₂R₈,





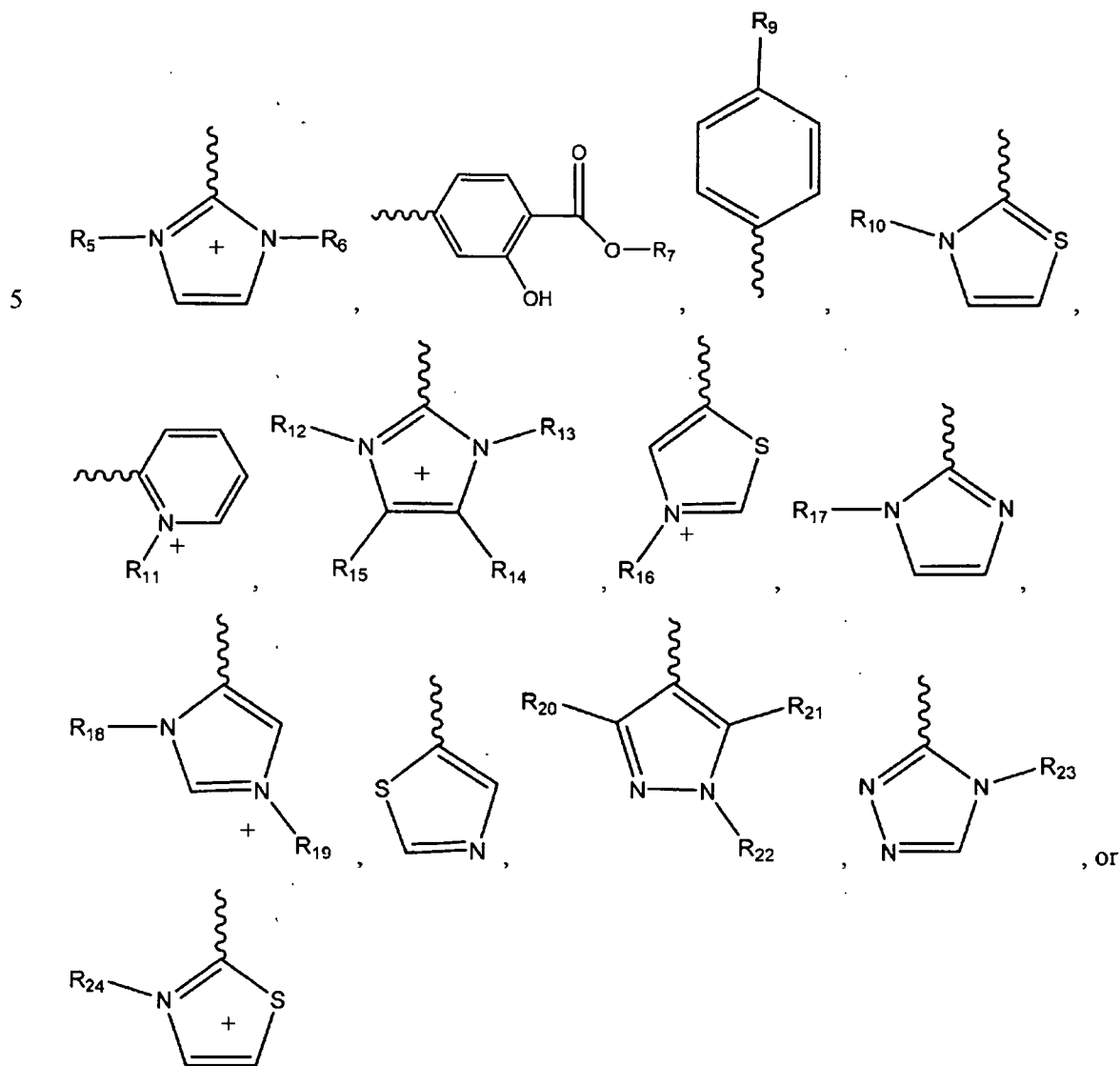
Each R₅, R₆, R₇, R₈, R₉, R₁₀, R₁₁, R₁₂, R₁₃, R₁₄, R₁₅, R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂, R₂₃, and R₂₄ may be the same or different and may each independently be hydrogen, halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, an unsubstituted or substituted alkyl, unsubstituted or substituted heteroalkyl, unsubstituted or substituted cycloalkyl, unsubstituted or substituted heterocycloalkyl, unsubstituted or substituted aryl, and an unsubstituted or substituted heteroaryl. R₂₅ may be an unsubstituted alkyl such as C₁₋₁₀ alkyl (e.g., CH₃).

[0009] The injury may be associated with an organ in the subject. Specifically, the organ may be skin, lungs, nose, esophagus, trachea, or bronchi. The alkylating agent may be a sulfur mustard, chlorine gas, phosgene, and 2-chloroethyl ethyl sulfide. Specifically, the alkylating agent is a sulfur mustard. Exposure to the alkylating agent may produce mitochondrial dysfunction, which in turn may result in an increase in reactive oxygen species production or oxidative stress. In particular, exposure to the alkylating agent, relative to non-exposure to the alkylating agent causes an increase in lactate dehydrogenase (LDH) levels, an increase in IgM levels, a decrease of glutathione levels, and an increase in myeloperoxidase levels.

[0010] The compound may be administered by inhalation administration, topical administration, intravenous administration, subcutaneous administration, intraperitoneal administration, and intramuscular administration. The compound may be administered to the subject within about 0.5 hours to about 48 hours after exposure to the alkylating agent. More specifically, the compound may be administered to the subject within about 1 hour to about 10 hours after exposure to the alkylating agent.

[0011] According to another aspect of the invention, a method of protecting a subject from the toxic effects associated with exposure to an alkylating agent includes administering to a subject in need thereof an effective amount of a compound of Formula

$R_1, R_2, R_3,$ and R_4 may each independently be $-H, -CF_3, -CO_2R_8,$



Each $R_5, R_6, R_7, R_8, R_9, R_{10}, R_{11}, R_{12}, R_{13}, R_{14}, R_{15}, R_{16}, R_{17}, R_{18}, R_{19}, R_{20}, R_{21}, R_{22}, R_{23},$ and R_{24} may be the same or different and may each independently be hydrogen, halogen, $-CN,$ $-CF_3, -OH, -NH_2, -COOH, -COOR_{25},$ an unsubstituted or substituted alkyl, unsubstituted or substituted heteroalkyl, unsubstituted or substituted cycloalkyl, unsubstituted or substituted heterocycloalkyl, unsubstituted or substituted aryl, and an unsubstituted or substituted heteroaryl. R_{25} may be an unsubstituted alkyl such as C_{1-10} alkyl (e.g., CH_3).

[0012] Additional features, advantages, and embodiments of the invention may be set forth or apparent from consideration of the following detailed description, and claims. Moreover, it is to be understood that both the foregoing summary of the invention and the following
5 detailed description are exemplary and intended to provide further explanation without limiting the scope of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The accompanying drawings, which are included to provide a further understanding of the invention, are incorporated in and constitute a part of this specification, illustrate
10 embodiments of the invention and together with the detailed description serve to explain the principles of the invention. No attempt is made to show structural details of the invention in more detail than may be necessary for a fundamental understanding of the invention and various ways in which it may be practiced.

[0014] FIGURE 1 shows the structures of bis(2-chloroethyl sulfide), known as SM, and its
15 analog chloroethyl ethyl sulfide (CEES).

[0015] FIGURE 2 is a graph showing that CEES exposure caused a concentration-dependent injury of human airway epithelial cells. Human lung 16HBE cells were grown to approximately 90% confluence and treated with concentrations of CEES ranging from 600 to 1000 μM for 24 h. Cell viability decreased in a dose-dependent manner as measured by
20 quantifying calcein AM fluorescence. Data represented as mean \pm S.E.M., $n = 4$ where control group fluorescence was defined as 100% viability.

[0016] FIGURE 3A-3C are graphs showing that CEES exposure produced increased levels of mitochondrial ROS dysfunction. SAE cells (Panel A) and 16HBE cells (Panel B) were treated with 900 μM CEES for 2, 4, 6, 8, 12, 24, and 48 h, after which cells were incubated
25 with the mitochondrial ROS probe MitoSOX (Panel A and Panel B) for 1 h. (Panel C) 16 HBE cells were incubated with the mitochondrial membrane potential indicator Rhodamine 123 for 30 min. MitoSOX fluorescence correlated with increased ROS, where Rhodamine 123 fluorescence was inversely correlated with mitochondrial membrane potential.

[0017] FIGURE 4 shows chemical structures the catalytic antioxidant metalloporphyrins
30 tested in specific examples 1-6, below.

[0018] FIGURE 5 is a graph showing the protective effects of metalloporphyrins on CEES-induced cell injury. 16HBE cells were grown to 90% confluence and exposed to 900 μM

CEES for a total of 24 h. Cells were treated 1 h after the initial CEES exposure with AEOL 10150, AEOL 10113, AEOL 10303, or MnTBAP at a final concentration of 50 μ M in the presence (black bars) or absence (white bars) of 900 μ M CEES. Data represented as mean \pm S.E.M., $n=4$. ***, $p<0.001$ compared with CEES-only treatment group.

5 [0019] FIGURE 6A-D are graphs showing the rescue effect of AEOL 10150 on CEES-induced cell death. SAE cells (Panel A and Panel B) and 16HBE cells (Panel C and Panel D) were exposed to 900 μ M CEES with AEOL 10150 at 10, 25, and 50 μ M concentrations added 1 h after CEES exposure. Cell viability was measured using both calcein AM (Panel A and Panel C) and MTT (Panel B and Panel D) staining with control values being defined as
10 100% viability. Data represented as mean \pm S.E.M., $n=4$. **, $p<0.01$; ***, $p<0.001$ compared with CEES-only treated group.

[0020] FIGURE 7A-C are graphs showing that AEOL 10150 rescues CEES-induced increases in mitochondrial ROS and dysfunction. SAE cells (Panel A) and 16HBE cells (Panel B) were exposed to 900 μ M CEES for 12 h. AEOL 10150 (50 μ M) was added 1 h
15 after CEES exposure. Panel C, 16HBE cells were exposed similar as before except for 4 h. Mitochondrial membrane potential was determined using Rhodamine 123, where fluorescence is inversely correlated with mitochondrial membrane potential. Mean fluorescence was normalized to control levels with controls being 100%. Data represents mean \pm S.E.M., $n=3$ to 6; *, $p<0.05$; ***, $p<0.001$ compared with control values. Two-way
20 ANOVA of AEOL 10150, $p=0.0563$; CEES, $p=0.0033$; interaction, $p=0.042$ (A); AEOL 10150, $p=0.1073$; CEES, $p=0.0004$; interaction, $p=0.0001$ (B); and AEOL 10150, $p=0.2876$; CEES, $p=0.0007$; interaction, $p=0.0051$ (C).

[0021] FIGURE 8A-B are graphs showing the effects of CEES on markers of cellular oxidative stress and prevention by AEOL 10150 in 16 HBE cells. Panel A: cells exposed to
25 900 μ M CEES for 12 h had decreased total cellular GSH levels, and AEOL 10150 (50 μ M) rescued this decrease when treated 1 h after CEES exposure. Total GSH levels were normalized to the amount of protein and expressed as nanomoles of GSH per milligram of protein. Panel B: CEES also increased the levels of the DNA oxidation marker 8OHdG, and AEOL 10150 (50 μ M) post-CEES treatment decreased the levels of DNA oxidation. Data
30 expressed as a ratio of 8OHdG per 10^5 2dG. Data presented as mean \pm S.E.M., $n=4$ to 8; *, $p<0.05$; ***, $p<0.001$ compared with control levels. Panel A: two-way ANOVA of AEOL 10150, $p=0.1444$; CEES, $p=0.0001$; interaction, $p=0.0481$; Panel B: two-way ANOVA of AEOL 10150, $p=0.1394$; CEES, $p=0.0001$; interaction, $p=0.0004$.

[0022] FIGURE 9A-D are graphs showing the effects of CEES on markers of injury, edema and inflammation and prevention by AEOL 10150 in rat lung. Panel A: the cytotoxicity marker lactate dehydrogenase (LDH) was measured spectrophotometrically. Panel B: protein levels which are a marker for edema were measured and was measured spectrophotometrically. Panel C: IgM, which is a marker of lung leak was measured by ELISA. Panel D: BAL cells, which are a marker of inflammation and hemorrhage were measure differential cytometry.

[0023] FIGURE 10 is a graph showing LDH levels in the BAL were increased as a result of CEES inhalation; these levels were decreased to control values when AEOL 10150 was given following CEES. Levels of LDH in the BAL leak were significantly increased as a result of CEES, indicative of epithelial damage and thus leak from those damaged cells. Post exposure treatment with AEOL 10150 significantly decreased LDH leak from cells. Data are shown as mean \pm S.E.M., protein $n=5$ to 9. **, $p < 0.01$; ***, $p < 0.001$.

[0024] FIGURE 11A-B are graphs showing the protective effect of AEOL 10150 on CEES-induced increases in BAL protein levels and BAL IgM. At 1 and 9 hours following CEES exposure, rats were treated with AEOL 10150 (5 mg/kg, SC). At 18 hours post exposure, rats were lavaged and levels of BAL protein and IgM were measured. Panel A: CEES exposure resulted in significant increases in BAL protein, while AEOL 10150 treatment with CEES exposure resulted in a significant decrease in protein in the BAL. Panel B: shows a significant increase in BAL IgM as a result of CEES exposure and a subsequent significant decrease in BAL IgM with AEOL 10150 treatment following CEES exposure. Data are shown as mean \pm S.E.M., protein $n=6$ to 16. ***, $p < 0.001$. IgM $n=6$. ***, $p < 0.001$.

[0025] FIGURE 12A-C are graphs showing that CEES inhalation resulted in increases in BAL RBCs and PMN; treatment with AEOL 10150 reduced BAL RBCs and PMN in BAL. Panel A: In EtOH+PBS or EtOH+AEOL 10150 treated rats, there were very low levels of RBCs. In the CEES+PBS group, rats had significantly increased RBCs in the BAL, indicative of hemorrhagic injury. Panel B: Neutrophils (polymorphonuclear cells, PMN) were also significantly increased in CEES+PBS treated rats as compared to both EtOH treatment groups. Treatment with AEOL 10150 following CEES resulted in significant decreases in PMN as compared to CEES+PBS. Macrophages were not significantly changed in any of the treatment groups. Data are mean \pm S.E.M., $n=6$ to 13. *, $p=0.05$; **, $p < 0.01$; ***, $p < 0.001$.

[0026] FIGURE 13 is a graph showing that lung tissue myeloperoxidase levels were significantly increased in the CEES+PBS group; treatment with AEOL 10150 significantly decreased lung myeloperoxidase levels as compared to CEES+PBS. Lung tissue was perfused and snap frozen at the time of euthanization. Lung tissue was homogenized in HTAB buffer. Oxidation of tetramethylbenzidine (TMB) was followed for 3 minutes; this data was used to calculate a rate of change. An extinction coefficient for TMB of $3.9 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$ at 652 nm was used to calculate Units of peroxidase activity and activity was normalized to protein levels using the BCA protein assay. Data are shown as mean \pm S.E.M., $n=6$. *, $p=0.05$; **, $p<0.01$.

10 [0027] FIGURE 14 is a graph showing that the DNA oxidation marker 8-hydroxydeoxyguanosine (8-OHdG) was significantly increased as a result of CEES inhalation; treatment with AEOL 10150 significantly decreased CEES-induced DNA oxidation. Data are shown as mean \pm S.E.M., $n=12$. *, $p=0.05$; **, $p<0.01$.

15 [0028] FIGURE 15 is a graph showing that levels of the lipid peroxidation marker 4-hydroxynonenal (4-HNE) were elevated as a result of CEES exposure, treatment with AEOL 10150 significantly decreased levels of 4-HNE. Data are shown as mean \pm S.E.M., $n=11$ for EtOH+PBS and CEES+PBS, $n=5$ for EtOH+10150 and CEES+10150. *, $p=0.05$; **.

DETAILED DESCRIPTION OF THE INVENTION

[0029] It is understood that the invention is not limited to the particular methodology, protocols, and reagents, etc., described herein, as these may vary as the skilled artisan will recognize. It is also to be understood that the terminology used herein is used for the purpose of describing particular embodiments only, and is not intended to limit the scope of the invention. It also is to be noted that as used herein and in the appended claims, the singular forms "a," "an," and "the" include the plural reference unless the context clearly dictates otherwise. Thus, for example, a reference to "a cell" is a reference to one or more cells and equivalents thereof known to those skilled in the art.

[0030] Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art to which the invention pertains. The embodiments of the invention and the various features and advantageous details thereof are explained more fully with reference to the non-limiting embodiments and examples that are described and/or illustrated in the accompanying drawings and detailed in the following description. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale, and features of one embodiment

may be employed with other embodiments as the skilled artisan would recognize, even if not explicitly stated herein. Descriptions of well-known components and processing techniques may be omitted so as to not unnecessarily obscure the embodiments of the invention. The examples used herein are intended merely to facilitate an understanding of ways in which the invention may be practiced and to further enable those of skill in the art to practice the
5 embodiments of the invention. Accordingly, the examples and embodiments herein should not be construed as limiting the scope of the invention, which is defined solely by the appended claims and applicable law.

[0031] Accordingly, provided immediately below is a "Definition" section, where certain
10 terms related to the invention are defined specifically for clarity, but all of the definitions are consistent with how a skilled artisan would understand these terms. Particular methods, devices, and materials are described, although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the invention. All references referred to herein are incorporated by reference herein in their entirety.

15 [0032] SM is sulfur mustard

[0033] CEES is 2-chloroethyl ethyl sulfide

[0034] SOD is superoxide dismutase

[0035] ROS is reactive oxygen species

[0036] RNS is reactive nitrogen species

20 [0037] GSH is glutathione

[0038] 8OHdG is 8-hydroxydeoxyguanosine

[0039] MTT is 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide

[0040] ANOVA is analysis of variance

[0041] HBE is human bronchiolar epithelial cells

25 [0042] SAEC is human small airway epithelial cells

[0043] 4-HNE is 4-hydroxynonenal

[0044] "Alkylating agent," as used herein, generally refers to compounds containing alkyl groups that combine readily with other molecules. For example, alkylating agents typically contain alkyl groups that readily attach to other molecules thereby forming a covalent bond.

This process may also be referred to as alkylation. Generally, alkylating agents can disrupt DNA function through different mechanisms, such as: (i) by alkylating DNA bases, thereby preventing DNA synthesis and RNA transcription, (ii) by mediating the formation of cross-bridges, bonds between atoms in the DNA strand, or (iii) by facilitating the mispairing of the nucleotides in the DNA strand thereby leading to mutations. Also, alkylating agents may initiate oxidative stress within the cells of the exposed organ system causing an overall decrease in intracellular glutathione (GSH) and increased DNA oxidation. Exposure to alkylating agents may cause blistering of the skin, damage to the eyes, and damage to the respiratory tract. Exposure to alkylating agents may also cause systemic toxic effects, such as nausea and vomiting, reduction in both leukocytes and erythrocytes, hemorrhagic tendencies, edema, depletion of glutathione, increased myeloperoxidase (MPO), increased lactate dehydrogenase (LDH), and increased IgM. Alkylating agents include, without limitation, the nitrogen mustards, including mechlorethamine hydrochloride, chlorambucil, busulfan, cyclophosphamide, and the sulfur mustards including chlorine gas, phosgene, and 2-chloroethyl ethyl sulfide.

[0045] "Oxidation," as used herein, is a chemical reaction that transfers electrons from a substance to an oxidizing agent. Oxidation reactions may produce free radicals, which result in oxidative stress and may ultimately result in cell death.

[0046] "Reactive oxygen species," as used herein, generally refers to free radicals, reactive anions containing oxygen atoms, or molecules containing oxygen atoms that can either produce free radicals or are chemically activated by them. Reactive oxygen species may include, without limitation, superoxide radicals, hydrogen peroxide, peroxy nitrite, lipid peroxides, hydroxyl radicals, thiyl radicals, superoxide anion, organic hydroperoxide, RO• alkoxy and ROO• peroxy radicals, and hypochlorous acid. The main source of reactive oxygen species (ROS) *in vivo* is aerobic respiration, although reactive oxygen species are also produced by peroxisomal β -oxidation of fatty acids, microsomal cytochrome P450 metabolism of xenobiotic compounds, stimulation of phagocytosis by pathogens or lipopolysaccharides, arginine metabolism, tissue specific enzymes. Accumulating oxidative damage may also affect the efficiency of mitochondria and further increase the rate of ROS production.

[0047] "Reactive nitrogen species," as used herein, generally refers to a family of biomolecules derived from nitric oxide (NO•) and may be produced in animals through the reaction of nitric oxide (NO•) with superoxide (O₂⁻) to form peroxy nitrite (ONOO⁻). In

general, reactive nitrogen species act together with reactive oxygen species to damage cells, resulting in nitrosative stress.

[0048] "Oxidative stress," as used herein, generally refers to cell damage caused by ROS. The primary damage to cells results from the ROS-induced alteration of macromolecules
5 such as polyunsaturated fatty acids in membrane lipids, essential proteins and DNA. As described in U.S. Patent No. 7,189,707, oxidative stress and ROS have been implicated in a number of disease states such as Alzheimer's disease, cancer, diabetes mellitus, and aging.

[0049] "Antioxidant," as used herein, generally refers to molecules or compounds with the capability to attenuate or prevent the oxidation of other molecules. Antioxidants may remove
10 free radicals generated from oxidation reaction and inhibit other oxidation reactions by becoming oxidized themselves. Antioxidants may include reducing agents such as thiols or polyphenols. Additionally, antioxidants may include, without limitation, glutathione, vitamin C, vitamin E, catalase, superoxide dismutase, glutathione peroxidase, various other peroxidases, the substituted porphyrin compounds of the invention and any other molecule or
15 compound that is capable of scavenging reactive oxygen species known in the art.

[0050] "Rescue," as used herein, is generally defined as counteracting, recovering, or conferring protection from the deleterious effects of reactive oxygen species and other free radicals in a subject, organ, tissue, cell, or biomolecule.

[0051] "Organ," as used herein, generally refers to a tissue that performs a specific function
20 or group of functions within an organism. An exemplary list of organs includes lungs, heart, blood vessels, blood, salivary glands, esophagus, stomach, liver, gallbladder, pancreas, intestines, rectum, anus, endocrine glands such as hypothalamus, pituitary or pituitary gland, pineal body or pineal gland, thyroid, parathyroids, adrenals, skin, hair, nails, lymph, lymph nodes, tonsils, adenoids, thymus, spleen, muscles, brain, spinal cord, peripheral nerves,
25 nerves, sex organs such as ovaries, fallopian tubes, uterus, vagina, mammary glands, testes, vas deferens, seminal vesicles, prostate, and penis, pharynx, larynx, trachea, bronchi, diaphragm, bones, cartilage, ligaments, tendons, kidneys, ureters, bladder, and urethra.

[0052] "Organ system," as used herein, generally refers to a group of related organs. Organ systems include, without limitation, circulatory system, digestive system, endocrine system,
30 integumentary system, lymphatic system, muscular system, nervous system, reproductive system, respiratory system, skeletal system, and urinary system.

[0053] "Biomarker," as used herein, generally refers to an organic biomolecule which is differentially present in a sample taken from a subject of one phenotypic status (e.g., exposure to an alkylating agent) as compared with another phenotypic status (e.g., no exposure to an alkylating agent). A biomarker is differentially present between different phenotypic statuses if the mean or median expression level of the biomarker in the different groups is calculated to be statistically significant. Common tests for statistical significance include, among others, t-test, ANOVA, Kruskal-Wallis, Wilcoxon, Mann-Whitney and odds ratio. Biomarkers, alone or in combination, provide measures of relative risk that a subject belongs to one phenotypic status or another. As such, they are useful as markers for disease (diagnostics), therapeutic effectiveness of a drug (theranostics), and for drug toxicity.

[0054] "Subject," as used herein, includes individuals who require intervention or manipulation due to a exposure or potential exposure to an alkylating agent that can facilitate organ injury. Furthermore, the term "subject" includes non-human animals and humans.

[0055] "Active agent," as used herein, generally refers to any compound capable of inducing a change in the phenotype or genotype of a cell, tissue, organ, or organism when contacted with the cell, tissue, organ, or organism. For example, the compound may have the ability to scavenge ROS, prevent or attenuate oxidative stress, and protect organs and organ systems from injury due to exposure to an alkylating agent. The compound may include any substituted porphyrin compounds of the invention, such as a superoxide mimetic, a catalase mimetic or a mimetic having both features.

[0056] A "pharmaceutically acceptable carrier," as used herein, generally refers to pharmaceutical excipients, for example, pharmaceutically, physiologically, acceptable organic or inorganic carrier substances suitable for enteral or parenteral application that do not deleteriously react with the active agent.

[0057] Where substituent groups are specified by their conventional chemical formulae, written from left to right, they equally encompass the chemically identical substituents that would result from writing the structure from right to left, e.g., $-\text{CH}_2\text{O}-$ is equivalent to $-\text{OCH}_2-$.

[0058] The term "alkyl," by itself or as part of another substituent, means, unless otherwise stated, a straight (i.e., unbranched) or branched carbon chain, or combination thereof, which may be fully saturated, mono- or polyunsaturated and can include di- and multivalent radicals, having the number of carbon atoms designated (i.e., $\text{C}_1\text{-C}_{10}$ means one to ten

carbons). Examples of saturated hydrocarbon radicals include, but are not limited to, groups such as methyl, ethyl, n-propyl, isopropyl, n-butyl, t-butyl, isobutyl, sec-butyl, (cyclohexyl)methyl, homologs and isomers of, for example, n-pentyl, n-hexyl, n-heptyl, n-octyl, and the like. An unsaturated alkyl group is one having one or more double bonds or
 5 triple bonds. Examples of unsaturated alkyl groups include, but are not limited to, vinyl, 2-propenyl, crotyl, 2-isopentenyl, 2-(butadienyl), 2,4-pentadienyl, 3-(1,4-pentadienyl), ethynyl, 1- and 3-propynyl, 3-butylnyl, and the higher homologs and isomers. An alkoxy is an alkyl attached to the remainder of the molecule via an oxygen linker (-O-).

[0059] The term "alkylene," by itself or as part of another substituent, means, unless
 10 otherwise stated, a divalent radical derived from an alkyl, as exemplified, but not limited by, -CH₂CH₂CH₂CH₂-. Typically, an alkyl (or alkylene) group will have from 1 to 24 carbon atoms, with those groups having 10 or fewer carbon atoms being preferred in the invention. A "lower alkyl" or "lower alkylene" is a shorter chain alkyl or alkylene group, generally having eight or fewer carbon atoms.

[0060] The term "heteroalkyl," by itself or in combination with another term, means, unless
 15 otherwise stated, a stable straight or branched chain, or combinations thereof, consisting of at least one carbon atom and at least one heteroatom selected from the group consisting of O, N, P, Si, and S, and wherein the nitrogen and sulfur atoms may optionally be oxidized, and the nitrogen heteroatom may optionally be quaternized. The heteroatom(s) O, N, P, S, and Si
 20 may be placed at any interior position of the heteroalkyl group or at the position at which the alkyl group is attached to the remainder of the molecule. Examples include, but are not limited to: -CH₂-CH₂-O-CH₃, -CH₂-CH₂-NH-CH₃, -CH₂-CH₂-N(CH₃)-CH₃, -CH₂-S-CH₂-CH₃, -CH₂-CH₂, -S(O)-CH₃, -CH₂-CH₂-S(O)₂-CH₃, -CH=CH-O-CH₃, -Si(CH₃)₃, -CH₂-CH=N-OCH₃, -CH=CH-N(CH₃)-CH₃, -O-CH₃, -O-CH₂-CH₃, and -CN. Up
 25 to two heteroatoms may be consecutive, such as, for example, -CH₂-NH-OCH₃.

[0061] Similarly, the term "heteroalkylene," by itself or as part of another substituent, means, unless otherwise stated, a divalent radical derived from heteroalkyl, as exemplified, but not limited by, -CH₂-CH₂-S-CH₂-CH₂- and -CH₂-S-CH₂-CH₂-NH-CH₂-. For
 heteroalkylene groups, heteroatoms can also occupy either or both of the chain termini (e.g.,
 30 alkyleneoxy, alkylenedioxy, alkyleneamino, alkylenediamino, and the like). Still further, for alkylene and heteroalkylene linking groups, no orientation of the linking group is implied by the direction in which the formula of the linking group is written. For example, the formula -C(O)₂R'- represents both -C(O)₂R'- and -R'C(O)₂-. As described above, heteroalkyl groups,

as used herein, include those groups that are attached to the remainder of the molecule through a heteroatom, such as -C(O)R', -C(O)NR', -NR'R", -OR', -SR', and/or -SO₂R'. Where "heteroalkyl" is recited, followed by recitations of specific heteroalkyl groups, such as -NR'R" or the like, it will be understood that the terms heteroalkyl and -NR'R" are not
5 redundant or mutually exclusive. Rather, the specific heteroalkyl groups are recited to add clarity. Thus, the term "heteroalkyl" should not be interpreted herein as excluding specific heteroalkyl groups, such as -NR'R" or the like.

[0062] The terms "cycloalkyl" and "heterocycloalkyl," by themselves or in combination with other terms, mean, unless otherwise stated, cyclic versions of "alkyl" and "heteroalkyl,"
10 respectively. Additionally, for heterocycloalkyl, a heteroatom can occupy the position at which the heterocycle is attached to the remainder of the molecule. Examples of cycloalkyl include, but are not limited to, cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl, 1-cyclohexenyl, 3-cyclohexenyl, cycloheptyl, and the like. Examples of heterocycloalkyl include, but are not limited to, 1-(1,2,5,6-tetrahydropyridyl), 1-piperidinyl, 2-piperidinyl, 3-
15 piperidinyl, 4-morpholinyl, 3-morpholinyl, tetrahydrofuran-2-yl, tetrahydrofuran-3-yl, tetrahydrothien-2-yl, tetrahydrothien-3-yl, 1-piperazinyl, 2-piperazinyl, and the like. A "cycloalkylene" and a "heterocycloalkylene," alone or as part of another substituent, means a divalent radical derived from a cycloalkyl and heterocycloalkyl, respectively.

[0063] The terms "halo" or "halogen," by themselves or as part of another substituent,
20 mean, unless otherwise stated, a fluorine, chlorine, bromine, or iodine atom. Additionally, terms such as "haloalkyl" are meant to include monohaloalkyl and polyhaloalkyl. For example, the term "halo(C₁-C₄)alkyl" includes, but is not limited to, fluoromethyl, difluoromethyl, trifluoromethyl, 2,2,2-trifluoroethyl, 4-chlorobutyl, 3-bromopropyl, and the like.

[0064] The term "acyl" means, unless otherwise stated, -C(O)R where R is a substituted or
25 unsubstituted alkyl, substituted or unsubstituted cycloalkyl, substituted or unsubstituted heteroalkyl, substituted or unsubstituted heterocycloalkyl, substituted or unsubstituted aryl, or substituted or unsubstituted heteroaryl.

[0065] The term "aryl" means, unless otherwise stated, a polyunsaturated, aromatic,
30 hydrocarbon substituent, which can be a single ring or multiple rings (preferably from 1 to 3 rings) that are fused together (i.e., a fused ring aryl) or linked covalently. A fused ring aryl refers to multiple rings fused together wherein at least one of the fused rings is an aryl ring. The term "heteroaryl" refers to aryl groups (or rings) that contain from one to four

heteroatoms selected from N, O, and S, wherein the nitrogen and sulfur atoms are optionally oxidized, and the nitrogen atom(s) are optionally quaternized. Thus, the term "heteroaryl" includes fused ring heteroaryl groups (i.e., multiple rings fused together wherein at least one of the fused rings is a heteroaromatic ring). A 5,6-fused ring heteroarylene refers to two rings fused together, wherein one ring has 5 members and the other ring has 6 members, and wherein at least one ring is a heteroaryl ring. Likewise, a 6,6-fused ring heteroarylene refers to two rings fused together, wherein one ring has 6 members and the other ring has 6 members, and wherein at least one ring is a heteroaryl ring. And a 6,5-fused ring heteroarylene refers to two rings fused together, wherein one ring has 6 members and the other ring has 5 members, and wherein at least one ring is a heteroaryl ring. A heteroaryl group can be attached to the remainder of the molecule through a carbon or heteroatom. Non-limiting examples of aryl and heteroaryl groups include phenyl, 1-naphthyl, 2-naphthyl, 4-biphenyl, 1-pyrrolyl, 2-pyrrolyl, 3-pyrrolyl, 3-pyrazolyl, 2-imidazolyl, 4-imidazolyl, pyrazinyl, 2-oxazolyl, 4-oxazolyl, 2-phenyl-4-oxazolyl, 5-oxazolyl, 3-isoxazolyl, 4-isoxazolyl, 5-isoxazolyl, 2-thiazolyl, 4-thiazolyl, 5-thiazolyl, 2-furyl, 3-furyl, 2-thienyl, 3-thienyl, 2-pyridyl, 3-pyridyl, 4-pyridyl, 2-pyrimidyl, 4-pyrimidyl, 5-benzothiazolyl, purinyl, 2-benzimidazolyl, 5-indolyl, 1-isoquinolyl, 5-isoquinolyl, 2-quinoxaliny, 5-quinoxaliny, 3-quinolyl, and 6-quinolyl. Substituents for each of the above noted aryl and heteroaryl ring systems are selected from the group of acceptable substituents described below. An "arylene" and a "heteroarylene," alone or as part of another substituent, mean a divalent radical derived from an aryl and heteroaryl, respectively.

[0066] For brevity, the term "aryl" when used in combination with other terms (e.g., aryloxy, arylthioxy, arylalkyl) includes both aryl and heteroaryl rings as defined above. Thus, the term "arylalkyl" is meant to include those radicals in which an aryl group is attached to an alkyl group (e.g., benzyl, phenethyl, pyridylmethyl, and the like) including those alkyl groups in which a carbon atom (e.g., a methylene group) has been replaced by, for example, an oxygen atom (e.g., phenoxyethyl, 2-pyridyloxymethyl, 3-(1-naphthyloxy)propyl, and the like).

[0067] The term "oxo," as used herein, means an oxygen that is double bonded to a carbon atom.

[0068] The term "alkylsulfonyl," as used herein, means a moiety having the formula $-S(O_2)-R'$, where R' is an alkyl group as defined above. R' may have a specified number of carbons (e.g., "C₁-C₄ alkylsulfonyl").

[0069] Each of the above terms (e.g., "alkyl," "heteroalkyl," "aryl," and "heteroaryl") includes both substituted and unsubstituted forms of the indicated radical. Preferred substituents for each type of radical are provided below.

[0070] Substituents for the alkyl and heteroalkyl radicals (including those groups often referred to as alkylene, alkenyl, heteroalkylene, heteroalkenyl, alkynyl, cycloalkyl, heterocycloalkyl, cycloalkenyl, and heterocycloalkenyl) can be one or more of a variety of groups selected from, but not limited to, -OR', =O, =NR', =N-OR', -NR'R'', -SR', -halogen, -SiR'R''R''', -OC(O)R', -C(O)R', -CO₂R', -CONR'R'', -OC(O)NR'R'', -NR''C(O)R', -NR'-C(O)NR''R''', -NR''C(O)₂R', -NR-C(NR'R''R''')=NR''''', -NR-C(NR'R'')=NR''''', -S(O)R', -S(O)₂R', -S(O)₂NR'R'', -NRSO₂R', -CN, and -NO₂ in a number ranging from zero to (2m'+1), where m' is the total number of carbon atoms in such radical. R', R'', R''', and R'''' each preferably independently refer to hydrogen, substituted or unsubstituted heteroalkyl, substituted or unsubstituted cycloalkyl, substituted or unsubstituted heterocycloalkyl, substituted or unsubstituted aryl (e.g., aryl substituted with 1-3 halogens), substituted or unsubstituted alkyl, alkoxy, or thioalkoxy groups, or arylalkyl groups. When a compound of the invention includes more than one R group, for example, each of the R groups is independently selected as are each R', R'', R''', and R'''' group when more than one of these groups is present. When R' and R'' are attached to the same nitrogen atom, they can be combined with the nitrogen atom to form a 4-, 5-, 6-, or 7-membered ring. For example, -NR'R'' includes, but is not limited to, 1-pyrrolidinyl and 4-morpholinyl. From the above discussion of substituents, one of skill in the art will understand that the term "alkyl" is meant to include groups including carbon atoms bound to groups other than hydrogen groups, such as haloalkyl (e.g., -CF₃ and -CH₂CF₃) and acyl (e.g., -C(O)CH₃, -C(O)CF₃, -C(O)CH₂OCH₃, and the like).

[0071] Similar to the substituents described for the alkyl radical, substituents for the aryl and heteroaryl groups are varied and are selected from, for example: -OR', -NR'R'', -SR', -halogen, -SiR'R''R''', -OC(O)R', -C(O)R', -CO₂R', -CONR'R'', -OC(O)NR'R'', -NR''C(O)R', -NR'-C(O)NR''R''', -NR''C(O)₂R', -NR-C(NR'R''R''')=NR''''', -NR-C(NR'R'')=NR''''', -S(O)R', -S(O)₂R', -S(O)₂NR'R'', -NRSO₂R', -CN, -NO₂, -R', -N₃, -CH(Ph)₂, fluoro(C₁-C₄)alkoxy, and fluoro(C₁-C₄)alkyl, in a number ranging from zero to the total number of open valences on the aromatic ring system; and where R', R'', R''', and R'''' are preferably independently selected from hydrogen, substituted or unsubstituted alkyl, substituted or unsubstituted heteroalkyl, substituted or unsubstituted cycloalkyl, substituted or unsubstituted

heterocycloalkyl, substituted or unsubstituted aryl, and substituted or unsubstituted heteroaryl. When a compound of the invention includes more than one R group, for example, each of the R groups is independently selected as are each R', R'', R''', and R'''' groups when more than one of these groups is present.

5 [0072] Two or more substituents may optionally be joined to form aryl, heteroaryl, cycloalkyl, or heterocycloalkyl groups. Such so-called ring-forming substituents are typically, though not necessarily, found attached to a cyclic base structure. In one embodiment, the ring-forming substituents are attached to adjacent members of the base structure. For example, two ring-forming substituents attached to adjacent members of a
10 cyclic base structure create a fused ring structure. In another embodiment, the ring-forming substituents are attached to a single member of the base structure. For example, two ring-forming substituents attached to a single member of a cyclic base structure create a spirocyclic structure. In yet another embodiment, the ring-forming substituents are attached to non-adjacent members of the base structure.

15 [0073] Two of the substituents on adjacent atoms of the aryl or heteroaryl ring may optionally form a ring of the formula $-T-C(O)-(CRR')_q-U-$, wherein T and U are independently $-NR-$, $-O-$, $-CRR'-$, or a single bond, and q is an integer of from 0 to 3. Alternatively, two of the substituents on adjacent atoms of the aryl or heteroaryl ring may optionally be replaced with a substituent of the formula $-A-(CH_2)_r-B-$, wherein A and B are
20 independently $-CRR'-$, $-O-$, $-NR-$, $-S-$, $-S(O)-$, $-S(O)_2-$, $-S(O)_2NR'-$, or a single bond, and r is an integer of from 1 to 4. One of the single bonds of the new ring so formed may optionally be replaced with a double bond. Alternatively, two of the substituents on adjacent atoms of the aryl or heteroaryl ring may optionally be replaced with a substituent of the formula $-(CRR')_s-X'-(C''R''')_d-$, where s and d are independently integers of from 0 to 3, and X' is $-O-$,
25 $-NR'-$, $-S-$, $-S(O)-$, $-S(O)_2-$, or $-S(O)_2NR'-$. The substituents R, R', R'', and R''' are preferably independently selected from hydrogen, substituted or unsubstituted alkyl, substituted or unsubstituted cycloalkyl, substituted or unsubstituted heterocycloalkyl, substituted or unsubstituted aryl, and substituted or unsubstituted heteroaryl.

[0074] As used herein, the terms "heteroatom" or "ring heteroatom" are meant to include
30 oxygen (O), nitrogen (N), sulfur (S), phosphorus (P), and silicon (Si).

[0075] A "substituent group," as used herein, means a group selected from the following moieties:

[0076] (A) -OH, -NH₂, -SH, -CN, -CF₃, -NO₂, oxo, halogen, unsubstituted alkyl, unsubstituted heteroalkyl, unsubstituted cycloalkyl, unsubstituted heterocycloalkyl, unsubstituted aryl, unsubstituted heteroaryl, and

[0077] (B) alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, and heteroaryl, substituted with at least one substituent selected from:

[0078] (i) oxo, -OH, -NH₂, -SH, -CN, -CF₃, -NO₂, halogen, unsubstituted alkyl, unsubstituted heteroalkyl, unsubstituted cycloalkyl, unsubstituted heterocycloalkyl, unsubstituted aryl, unsubstituted heteroaryl, and

[0079] (ii) alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, and heteroaryl, substituted with at least one substituent selected from:

[0080] (a) oxo, -OH, -NH₂, -SH, -CN, -CF₃, -NO₂, halogen, unsubstituted alkyl, unsubstituted heteroalkyl, unsubstituted cycloalkyl, unsubstituted heterocycloalkyl, unsubstituted aryl, unsubstituted heteroaryl, and

[0081] (b) alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, or heteroaryl, substituted with at least one substituent selected from: oxo, -OH, -NH₂, -SH, -CN, -CF₃, -NO₂, halogen, unsubstituted alkyl, unsubstituted heteroalkyl, unsubstituted cycloalkyl, unsubstituted heterocycloalkyl, unsubstituted aryl, and unsubstituted heteroaryl.

[0082] A "size-limited substituent" or "size-limited substituent group," as used herein, means a group selected from all of the substituents described above for a "substituent group," wherein each substituted or unsubstituted alkyl is a substituted or unsubstituted C₁-C₂₀ alkyl, each substituted or unsubstituted heteroalkyl is a substituted or unsubstituted 2 to 20 membered heteroalkyl, each substituted or unsubstituted cycloalkyl is a substituted or unsubstituted C₄-C₈ cycloalkyl, and each substituted or unsubstituted heterocycloalkyl is a substituted or unsubstituted 4 to 8 membered heterocycloalkyl.

[0083] A "lower substituent" or "lower substituent group," as used herein, means a group selected from all of the substituents described above for a "substituent group," wherein each substituted or unsubstituted alkyl is a substituted or unsubstituted C₁-C₈ alkyl, each substituted or unsubstituted heteroalkyl is a substituted or unsubstituted 2 to 8 membered heteroalkyl, each substituted or unsubstituted cycloalkyl is a substituted or unsubstituted C₃-C₇ cycloalkyl, and each substituted or unsubstituted heterocycloalkyl is a substituted or unsubstituted 5 to 7 membered heterocycloalkyl.

[0084] The term "pharmaceutically acceptable salts" is meant to include salts of the active compounds that are prepared with relatively nontoxic acids or bases, depending on the particular substituents found on the compounds described herein. When compounds of the invention contain relatively acidic functionalities, base addition salts can be obtained by
5 contacting the neutral form of such compounds with a sufficient amount of the desired base, either neat or in a suitable inert solvent. Examples of pharmaceutically acceptable base addition salts include sodium, potassium, calcium, ammonium, organic amino, or magnesium salt, or a similar salt. When compounds of the invention contain relatively basic
10 functionalities, acid addition salts can be obtained by contacting the neutral form of such compounds with a sufficient amount of the desired acid, either neat or in a suitable inert solvent. Examples of pharmaceutically acceptable acid addition salts include those derived from inorganic acids like hydrochloric, hydrobromic, nitric, carbonic,
monohydrogencarbonic, phosphoric, monohydrogenphosphoric, dihydrogenphosphoric, sulfuric, monohydrogensulfuric, hydriodic, or phosphorous acids and the like, as well as the
15 salts derived from relatively nontoxic organic acids like acetic, propionic, isobutyric, maleic, malonic, benzoic, succinic, suberic, fumaric, lactic, mandelic, phthalic, benzenesulfonic, p-tolylsulfonic, citric, tartaric, oxalic, methanesulfonic, and the like. Also included are salts of amino acids such as arginate and the like, and salts of organic acids like glucuronic or galacturonic acids and the like (*see*, for example, Berge *et al.*, "Pharmaceutical Salts",
20 *Journal of Pharmaceutical Science*, 1977, 66, 1-19). Certain specific compounds of the invention contain both basic and acidic functionalities that allow the compounds to be converted into either base or acid addition salts.

[0085] Thus, the compounds of the invention may exist as salts, such as with pharmaceutically acceptable acids. The invention includes such salts. Examples of such salts
25 include hydrochlorides, hydrobromides, sulfates, methanesulfonates, nitrates, maleates, acetates, citrates, fumarates, tartrates (e.g., (+)-tartrates, (-)-tartrates, or mixtures thereof including racemic mixtures), succinates, benzoates, and salts with amino acids such as glutamic acid. These salts may be prepared by methods known to those skilled in the art.

[0086] The neutral forms of the compounds are preferably regenerated by contacting the salt with a base or acid and isolating the parent compound in the conventional manner. The
30 parent form of the compound differs from the various salt forms in certain physical properties, such as solubility in polar solvents.

[0087] In addition to salt forms, the invention provides compounds in a prodrug form. Prodrugs of the compounds described herein are those compounds that readily undergo chemical changes under physiological conditions to provide the compounds of the invention. Additionally, prodrugs can be converted to the compounds of the invention by chemical or biochemical methods in an *ex vivo* environment. For example, prodrugs can be slowly converted to the compounds of the invention when placed in a transdermal patch reservoir with a suitable enzyme or chemical reagent.

[0088] Certain compounds of the invention can exist in unsolvated forms as well as solvated forms, including hydrated forms. In general, the solvated forms are equivalent to unsolvated forms and are encompassed within the scope of the invention. Certain compounds of the invention may exist in multiple crystalline or amorphous forms. In general, all physical forms are equivalent for the uses contemplated by the invention and are intended to be within the scope of the invention.

[0089] Certain compounds of the invention possess asymmetric carbon atoms (optical centers) or double bonds; the racemates, diastereomers, tautomers, geometric isomers, and individual isomers are encompassed within the scope of the invention. The compounds of the invention do not include those that are known in the art to be too unstable to synthesize and/or isolate.

[0090] The compounds of the invention may also contain unnatural proportions of atomic isotopes at one or more of the atoms that constitute such compounds. For example, the compounds may be radiolabeled with radioactive isotopes, such as for example tritium (^3H), iodine-125 (^{125}I), or carbon-14 (^{14}C). All isotopic variations of the compounds of the invention, whether radioactive or not, are encompassed within the scope of the invention.

[0091] The symbol “~” denotes the point of attachment of a chemical moiety to the remainder of a molecule or chemical formula.

[0092] “Effective dose” or “pharmaceutically effective dose,” as used herein, generally refers to the amount of the substituted porphyrin(s) described herein that produces a desired therapeutic effect, such as counteracting the deleterious effects of alkylating agent exposure. The precise amount of the effective dose of a such a compound will yield the most effective results in terms of efficacy of treatment in a given subject will depend upon the activity, pharmacokinetics, pharmacodynamics, and bioavailability of a particular substituted porphyrin of the invention, physiological condition of the subject, the nature of the

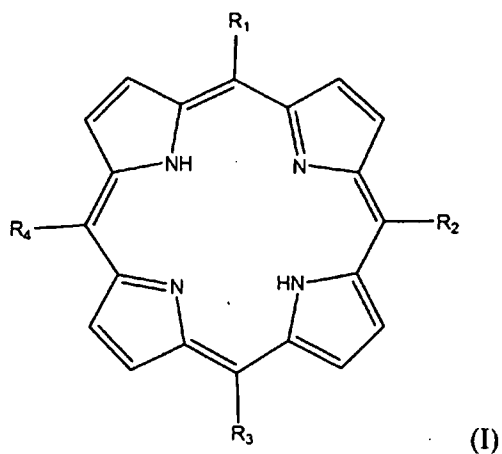
pharmaceutically acceptable carrier in a formulation, and a route of administration, among other potential factors. Those skilled in the clinical and pharmacological arts will be able to determine these factors through routine experimentation consisting of monitoring the subject and adjusting the dosage. Remington: The Science and Practice of Pharmacy (Gennaro ed. 5 20.sup.th edition, Williams & Wilkins PA, USA) (2000).

Methods

[0093] In one aspect, methods are provided for treating, rescuing and/or protecting organ and organ systems in a subject from the deleterious effects resulting from exposure to alkylating agents using substituted porphyrins. In one embodiment, a method for treating an 10 injury associated with exposure to an alkylating agent in a subject includes administering to a subject in need thereof an effective amount of a compound described below (also referred to herein as a “substituted porphyrin”). In another embodiment, a method for protecting a subject from the toxic effects associated with exposure to an alkylating agent includes administering prophylactically to a subject in need thereof an effective amount of a 15 compound described below (also referred to herein as a “substituted porphyrin”). In other embodiments, methods are provided for rescuing or protecting organ injury by administering substituted porphyrins such as substituted metalloporphyrins as the active agent of an alkylating agent protectant.

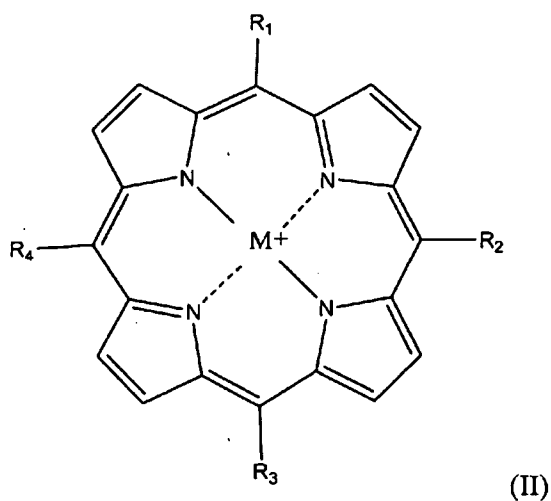
[0094] Compounds and compositions are provided herein that are suitable for such 20 methods. The compounds include low molecular weight substituted porphyrins, including substituted metalloporphyrins. In some embodiments, the compounds are capable of mimicking the action of endogenous antioxidants, such as superoxide dismutase (SOD) and catalase.

[0095] Useful substituted porphyrins include any of the porphyrin compounds disclosed in 25 U.S. Patent No. 7,189,707 and U.S. Patent Publication No. 2007/0149498, the contents of each reference are expressly incorporated herein in their entirety. In some embodiments, the substituted porphyrin is an imidazolium porphyrins. In one embodiment, the compound useful in the methods provided herein has the formula:

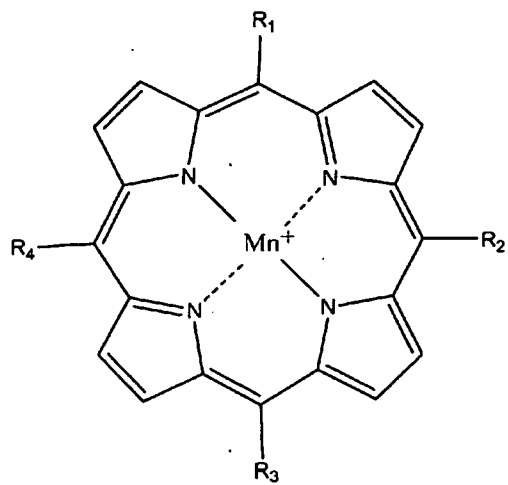


or a pharmaceutically acceptable salt thereof.

- [0096] In Formula I, the substituted porphyrin may be bound to a metal. In formula II, below, M is a metal which may include manganese, iron, cobalt, copper, nickel, zinc, and ions thereof and may have the formula:
- 5

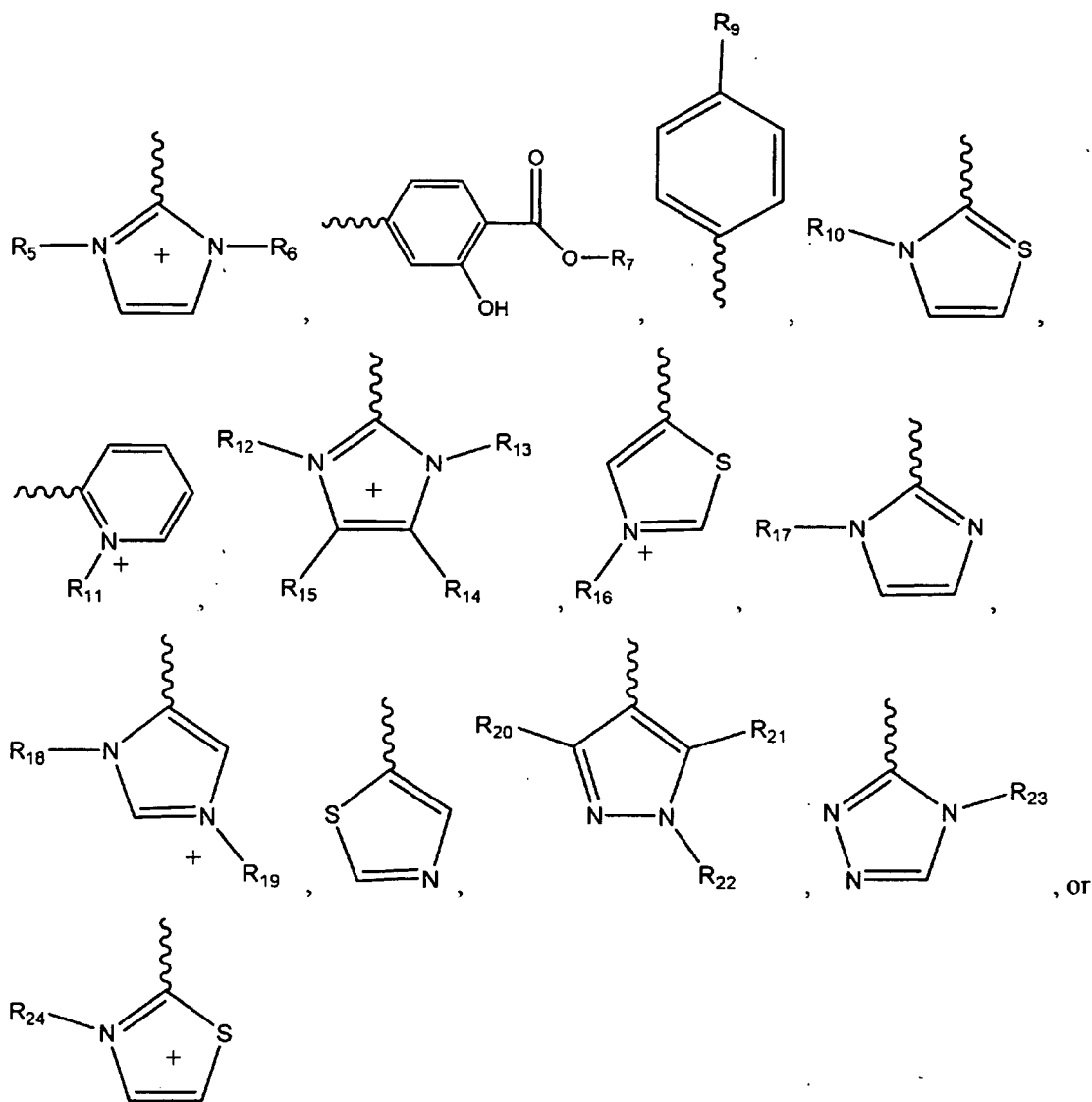


In a specific embodiment, the metal is manganese and has the formula:



(III).

[0097] $R_1, R_2, R_3,$ and R_4 may each independently be $-H, -CF_3, -CO_2R_8,$



5

[0098] Where $R_1, R_2, R_3,$ and R_4 contain a positive charge, one of skill will immediately recognize that an anionic compound or molecule will be present where the compound is in solution. Any applicable anionic compound or molecule may be used as a counterion to the positively charged substituents, including for example chloride, fluoride, sulfide, a sulfate, a carbonate, or a phosphate.

10

[0099] Each $R_5, R_6, R_7, R_8, R_9, R_{10}, R_{11}, R_{12}, R_{13}, R_{14}, R_{15}, R_{16}, R_{17}, R_{18}, R_{19}, R_{20}, R_{21}, R_{22}, R_{23},$ and R_{24} may be the same or different and may each independently be hydrogen, halogen, $-CN, -CF_3, -OH, -NH_2, -COOH, -COOR_{25},$ an unsubstituted or substituted alkyl, unsubstituted or substituted heteroalkyl, unsubstituted or substituted cycloalkyl, unsubstituted or substituted

heterocycloalkyl, unsubstituted or substituted aryl, and an unsubstituted or substituted heteroaryl. R₂₅ may be an unsubstituted alkyl such as C₁₋₁₀ alkyl (e.g., CH₃). In some embodiments, R₅, R₆, R₇, R₈, R₉, R₁₀, R₁₁, R₁₂, R₁₃, R₁₄, R₁₅, R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂, R₂₃, and R₂₄ may each independently be hydrogen, halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, substituted or unsubstituted C_{1-C10} (e.g., C_{1-C6}) alkyl, substituted or unsubstituted 2 to 10 membered (e.g., 2 to 6 membered) heteroalkyl, substituted or unsubstituted C_{3-C8} (e.g., C_{5-C7}) cycloalkyl, substituted or unsubstituted 3 to 8 membered (e.g., 3 to 6 membered) heterocycloalkyl, substituted or unsubstituted C_{5-C8} (e.g., C_{5-C6}) aryl, or substituted or unsubstituted 5 to 8 membered (e.g., 5 to 6 membered) heteroaryl. In some embodiments, one or more of R₅, R₆, R₇, R₈, R₉, R₁₀, R₁₁, R₁₂, R₁₃, R₁₄, R₁₅, R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂, R₂₃, and R₂₄ is unsubstituted. In one embodiment, R₅, R₆, R₇, R₈, R₉, R₁₀, R₁₁, R₁₂, R₁₃, R₁₄, R₁₅, R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂, R₂₃, and R₂₄ are independently hydrogen or a substituted or unsubstituted C_{1-C10} (e.g., C_{1-C6} or C_{1-C3}) alkyl.

[0100] In one embodiment, R₅, R₆, R₇, R₈, R₉, R₁₀, R₁₁, R₁₂, R₁₃, R₁₄, R₁₅, R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂, R₂₃, and R₂₄, may independently be hydrogen, halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, R₂₆-substituted or unsubstituted alkyl, R₂₆-substituted or unsubstituted heteroalkyl, R₂₆-substituted or unsubstituted cycloalkyl, R₂₆-substituted or unsubstituted heterocycloalkyl, R₂₆-substituted or unsubstituted aryl, or R₂₆-substituted or unsubstituted heteroaryl. R₂₆ is halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, R₂₇-substituted or unsubstituted alkyl, R₂₇-substituted or unsubstituted heteroalkyl, R₂₇-substituted or unsubstituted cycloalkyl, R₂₇-substituted or unsubstituted heterocycloalkyl, R₂₇-substituted or unsubstituted aryl, or R₂₇-substituted or unsubstituted heteroaryl. In one embodiment, R₂₆ is halogen, -CN, -CF₃, -OH, -NH₂, -COOH, R₂₇-substituted or unsubstituted C_{1-C10} (e.g., C_{1-C6}) alkyl, R₂₇-substituted or unsubstituted 2 to 10 membered (e.g., 2 to 6 membered) heteroalkyl, R₂₇-substituted or unsubstituted C_{3-C8} (e.g., C_{5-C7}) cycloalkyl, R₂₇-substituted or unsubstituted 3 to 8 membered (e.g., 3 to 6 membered) heterocycloalkyl, R₂₇-substituted or unsubstituted C_{5-C8} (e.g., C_{5-C6}) aryl, or R₂₇-substituted or unsubstituted 5 to 8 membered (e.g., 5 to 6 membered) heteroaryl.

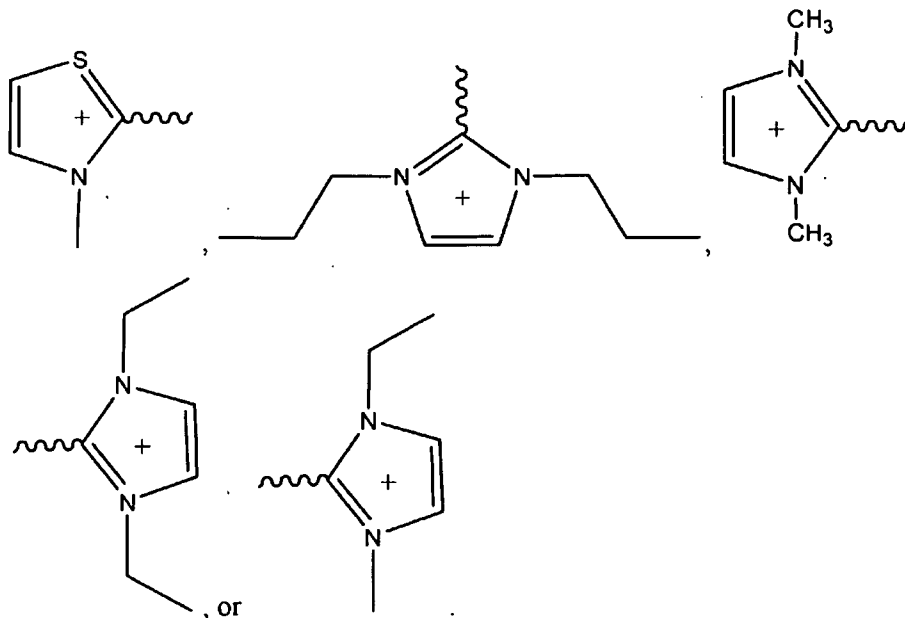
[0101] R₂₇ is halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, R₂₈-substituted or unsubstituted heteroalkyl, R₂₈-substituted or unsubstituted cycloalkyl, R₂₈-substituted or unsubstituted heterocycloalkyl, R₂₈-substituted or unsubstituted aryl, or R₂₈-substituted or unsubstituted heteroaryl. In one embodiment, R₂₇ is halogen, -CN, -CF₃, -OH, -NH₂, -COOH, R₂₈-substituted or unsubstituted C_{1-C10} (e.g., C_{1-C6}) alkyl, R₂₈-substituted or

unsubstituted 2 to 10 membered (e.g., 2 to 6 membered) heteroalkyl, R_{28} -substituted or unsubstituted C_3 - C_8 (e.g., C_5 - C_7) cycloalkyl, R_{28} -substituted or unsubstituted 3 to 8 membered (e.g., 3 to 6 membered) heterocycloalkyl, R_{28} -substituted or unsubstituted C_5 - C_8 (e.g., C_5 - C_6) aryl, or R_{28} -substituted or unsubstituted 5 to 8 membered (e.g., 5 to 6 membered) heteroaryl. R_{28} is halogen, -CN, -CF₃, -OH, -NH₂, -COOH, -COOR₂₅, unsubstituted alkyl, unsubstituted heteroalkyl, unsubstituted cycloalkyl, unsubstituted heterocycloalkyl, unsubstituted aryl, or unsubstituted heteroaryl.

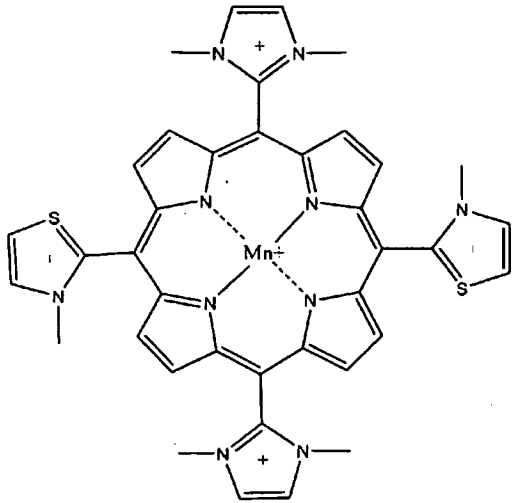
[0102] In one embodiment, R_{26} and/or R_{27} are substituted with a substituent group, a size-limited substituent group or a lower substituent group. In another embodiment, R_{27} and R_{28} are independently halogen, -CN, -CF₃, -OH, -NH₂, -COOH, COOR₂₅, unsubstituted C_1 - C_{10} (e.g., C_1 - C_6) alkyl, unsubstituted 2 to 10 membered (e.g., 2 to 6 membered) heteroalkyl, unsubstituted C_3 - C_8 (e.g., C_5 - C_7) cycloalkyl, unsubstituted 3 to 8 membered (e.g., 3 to 6 membered) heterocycloalkyl, unsubstituted C_5 - C_8 (e.g., C_5 - C_6) aryl, or unsubstituted 5 to 8 membered (e.g., 5 to 6 membered) heteroaryl.

[0103] In a particular embodiment, each R_5 , R_6 , R_7 , R_8 , R_9 , R_{10} , R_{11} , R_{12} , R_{13} , R_{14} , R_{15} , R_{16} , R_{17} , R_{18} , R_{19} , R_{20} , R_{21} , R_{22} , R_{23} , R_{24} , and R_{25} may be the same or different and may each independently be an alkyl, and particularly a C_{1-20} alkyl, more particularly a C_{1-10} alkyl, and even more particularly a C_{1-4} alkyl, and even more particularly, a methyl, an ethyl, or a propyl.

[0104] In a more specific embodiment, R_1 , R_2 , R_3 , and R_4 may each independently be

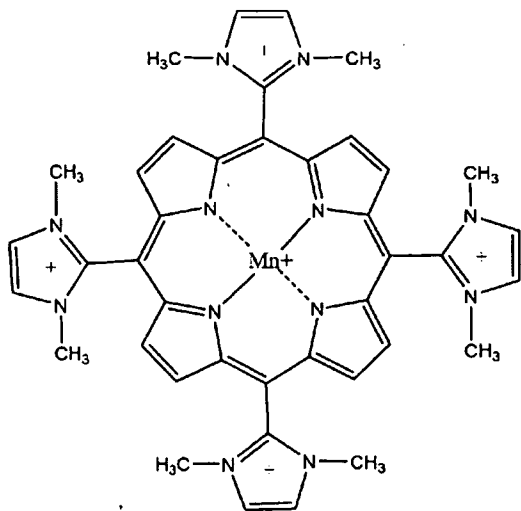
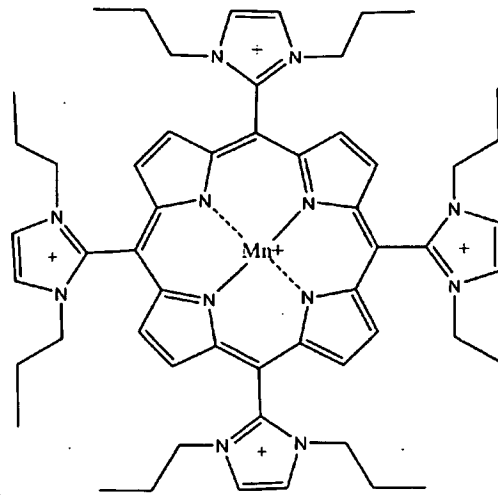


[0105] In a specific embodiment, the low molecule weight compound of the invention may have the formula:



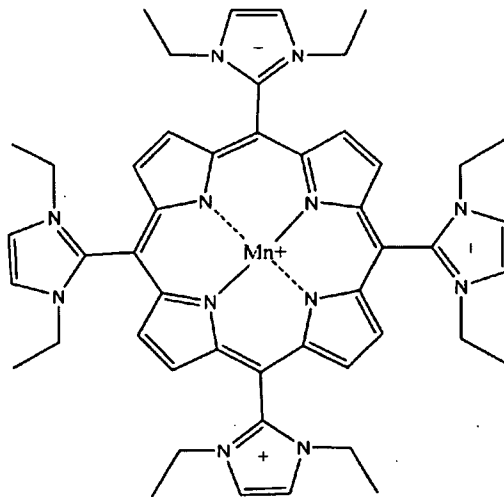
(V),

(IV),

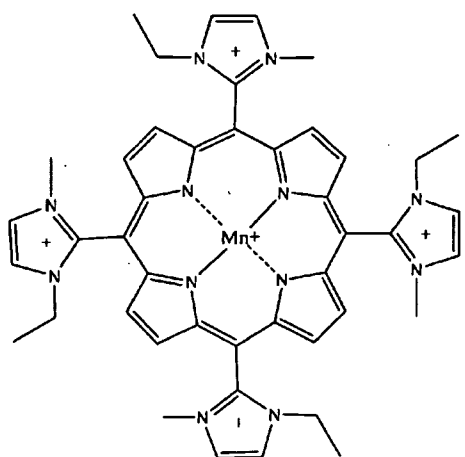


(VII), or

(VI),

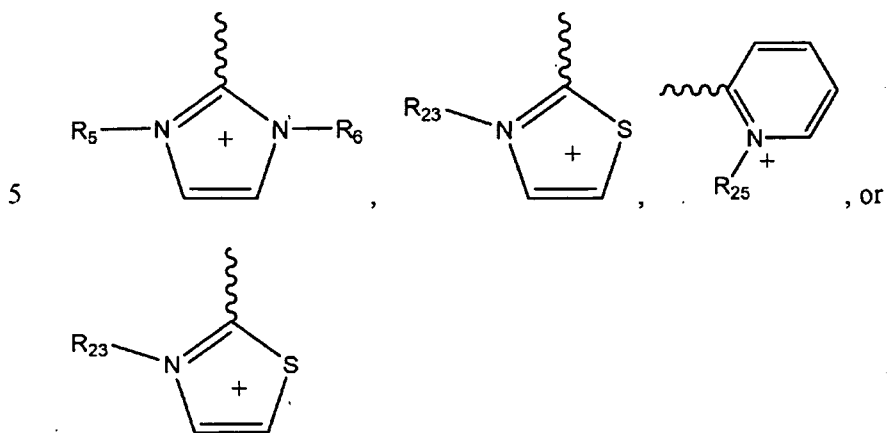


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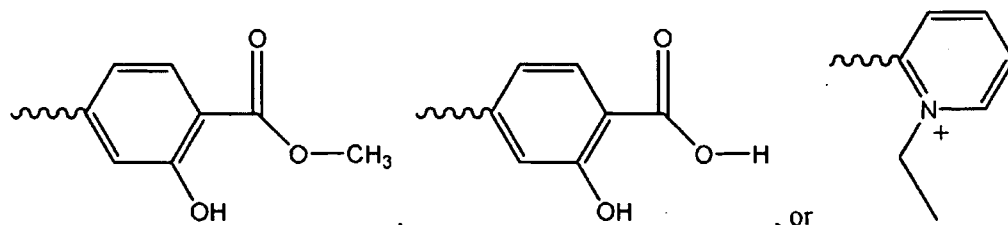


(VIII).

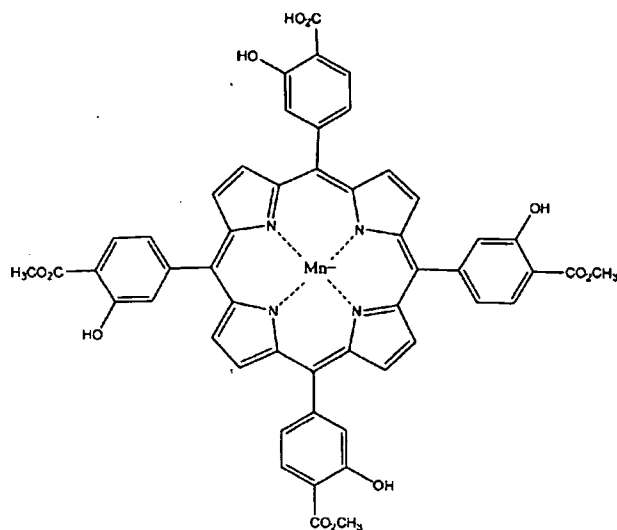
[0106] In another specific embodiment, R_1 , R_2 , R_3 , and R_4 may each independently be



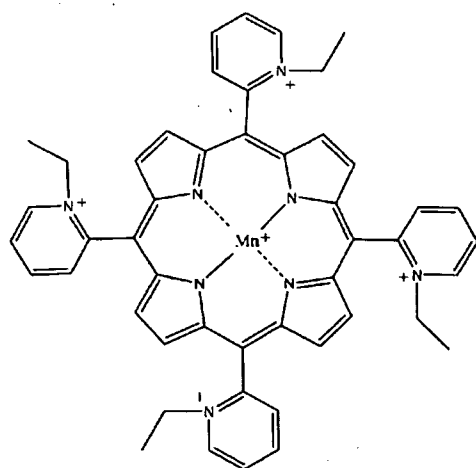
10 [0107] In another specific embodiment, R_1 , R_2 , R_3 , and R_4 may each independently be



[0108] In a further specific embodiment, substituted porphyrin compounds of the invention may have the formula:



(IX), or



(X).

- 5 [0109] In some embodiments, each substituted group described in the compounds above (e.g., Formulae (I)-(X)) is substituted with at least one substituent group. More specifically, in some embodiments, each substituted alkyl, substituted heteroalkyl, substituted cycloalkyl, substituted heterocycloalkyl, substituted aryl, substituted heteroaryl, described in the compounds above (e.g., Formulae (I)-(X)) are substituted with at least one substituent group.
- 10 In other embodiments, at least one or all of these groups are substituted with at least one size-limited substituent group. Alternatively, at least one or all of these groups are substituted with at least one lower substituent group.

- [0110] In other embodiments of the compounds described above (e.g., Formulae (I)-(X)) each substituted or unsubstituted alkyl is a substituted or unsubstituted C₁-C₂₀ alkyl, each substituted or unsubstituted heteroalkyl is a substituted or unsubstituted 2 to 20 membered
- 15

heteroalkyl, each substituted or unsubstituted cycloalkyl is a substituted or unsubstituted C₃-C₈ cycloalkyl, and each substituted or unsubstituted heterocycloalkyl is a substituted or unsubstituted 3 to 8 membered heterocycloalkyl.

[0111] In some embodiments, each substituted or unsubstituted alkyl is a substituted or unsubstituted C₁-C₈ alkyl, each substituted or unsubstituted heteroalkyl is a substituted or unsubstituted 2 to 8 membered heteroalkyl, each substituted or unsubstituted cycloalkyl is a substituted or unsubstituted C₅-C₇ cycloalkyl, and each substituted or unsubstituted heterocycloalkyl is a substituted or unsubstituted 5 to 7 membered heterocycloalkyl.

[0112] In another embodiment, the compounds are any one or all of the compounds set forth in Table 1, in the Examples section below.

Alkylating Agents

[0113] Alkylating agents contain alkyl groups that combine readily, typically through covalent bonding, with other molecules. Alkylating agents can disrupt DNA function by three mechanisms: (i) alkylating DNA bases, thereby preventing DNA synthesis and RNA transcription, (ii) mediating the formation of cross-bridges, bonds between atoms in the DNA strand, or (iii) facilitating the mis-pairing of the nucleotides in the DNA strand resulting in mutations in the DNA strand. Also, alkylating agents may initiate oxidative stress within the cells of the exposed organ system causing an overall decrease in intracellular glutathione (GSH) and increased DNA oxidation.

[0114] Alkylating agents include, without limitation, the nitrogen mustards, such as mechlorethamine hydrochloride, chlorambucil, busulfan, cyclophosphamide, and the sulfur mustards such as chlorine gas, phosgene, and 2-chloroethyl ethyl sulfide (CEES). Exposure to alkylating agents may cause blistering of the skin, damage to the eyes, and damage to the respiratory tract. Exposure to alkylating agents may also cause systemic toxic effects, such as nausea and vomiting, hemorrhagic tendencies, edema, and a reduction in both leukocytes and erythrocytes.

[0115] Sulfur mustard (2, 2'-dichloro diethyl sulfide) is a known potent vesicating agent and inhalation results in apoptosis and necrosis of the airway epithelium, inflammation, edema, and pseudomembrane formation. 2-chloroethyl ethyl sulfide (CEES, half mustard) is a monofunctional analog of SM that can be utilized to elucidate the mechanisms of injury and as an initial screening of therapeutics. Both SM and CEES (Figure 1) are alkylating agents capable of binding macromolecules including proteins, DNA and lipids.

[0116] Oxidative stress plays a significant role in SM/CEES mediated damage. For example, exposure to CEES causes an imbalance in production of ROS/RNS and antioxidant defenses in favor of the former. There are many factors that contribute to the increase in ROS following SM/CEES exposure. For example, exposure to SM/CEES facilitates the proliferation of inflammatory cells such as polymorphonuclear leukocytes (PMN), which in turn produces oxidants, including superoxide and hypochlorous acid (HOCl). Furthermore, exposure to CEES also results mitochondrial dysfunction which further drives increased ROS production, and ultimately, oxidative stress.

[0117] As discussed above, following exposure to SM/CEES, there is irreparable damage to the respiratory tract such as apoptosis and necrosis of the airway epithelium. However, in certain embodiments of the invention, administration of the substituted porphyrins of the invention subsequent to alkylating agent exposure, have been shown to significantly improve the outcome. For example, administration of the substituted porphyrins of the invention following CEES exposure have been shown to rescue lung cells and airway cells from alkylating agent-induced toxicity, prevent alkylating agent-mediated ROS and dysfunction, and alkylating agent-induced oxidative stress. In further embodiments, the substituted porphyrins of the invention have been shown to reduce alkylating agent-induced cytotoxicity, reduce alkylating agent-induced increases of protein and IgM in the lung, reduce levels of RBCs and inflammatory cells in the lung, decrease tissue accumulation of PMN, and prevent alkylating agent-induced oxidative stress.

Biomarkers of Alkylating Agents

[0118] A specific embodiment of the invention is directed to biomarkers that are characteristic of alkylating agent exposure. The biomarkers of alkylating agent exposure may include ROS such as superoxide radicals, hydrogen peroxide, peroxy nitrite, lipid peroxides, hydroxyl radicals, thiyl radicals, superoxide anion, organic hydroperoxide, RO• alkoxy and ROO• peroxy radicals, and hypochlorous acid, reactive nitrogen compounds, and compounds indicative of oxidative stress, such as lipid peroxidation products.

[0119] In a specific embodiment, biomarkers characteristic of exposure to the half mustard gas, CEES, include glutathione, myeloperoxidase (MPO), lactate dehydrogenase (LDH), IgM, 8-OHdG, 4-HNE, and increase in extracellular proteins which are associated with edema. Specifically, following CEES exposure, there is a depletion of glutathione, increased levels of myeloperoxidase (MPO), increased levels of LDH, increased levels of IgM, increased levels in markers of oxidized DNA such as 8-oxo-2dG, and increased levels in markers of lipid

oxidation such as 4-hydroxynonenal (4HNE). In certain aspects, the presence of increased LDH levels may be indicative of increased cytotoxicity, the presence of increased protein levels may be indicative of epithelial cell death, the presence of increased IgM levels may be indicative of increased vascular permeability, and the presence of MPO may be indicative of inflammatory response. Oxidative stress occurs when oxidant production exceeds antioxidant defense. Thus, one marker of oxidative damage is DNA oxidation, which can be measured by the formation of 8O-HdG. Another marker of oxidative damage is the formation of lipid peroxidation products including 4-hydroxynonenal (4-HNE).

[0120] In another embodiment of the invention, a biomarker profile following alkylating agent exposure may be used for determining therapeutic efficacy or toxicity of a compound. If the compound has a pharmaceutical impact on the subject, organ or cell following exposure to the alkylating agent, the phenotype (e.g., the pattern or profile) of the biomarkers changes towards a non-exposure profile. For example, glutathione is depleted following alkylating agent exposure and lactate dehydrogenase (LDH) is increased following alkylating agent exposure. Therefore, one can follow the course of the amounts of these biomarkers in the subject, organ, or cell during the course of treatment. Accordingly, this method involves measuring one or more biomarkers upon exposure to the alkylating agent. Methods for measuring the specific biomarkers are a matter of routine experimentation and are known by those of skill in the art and are described in U.S. Patent No. 7,189,707, which is expressly incorporated by reference in its entirety herein.

Formulations

[0121] In another embodiment, the invention provides pharmaceutical compositions comprising a low molecular weight substituted porphyrin compound of the invention or a low molecular weight substituted porphyrin in combination with a pharmaceutically acceptable excipient (e.g., carrier). Suitable pharmaceutically acceptable carriers include water, salt solutions (such as Ringer's solution), alcohols, oils, gelatins, and carbohydrates such as lactose, amylose or starch, fatty acid esters, hydroxymethylcellulose, and polyvinyl pyrrolidone. Such preparations can be sterilized and, if desired, mixed with auxiliary agents such as lubricants, preservatives, stabilizers, wetting agents, emulsifiers, salts for influencing osmotic pressure, buffers, coloring, and/or aromatic substances and the like that do not deleteriously react with the compounds of the invention.

[0122] The compounds of the invention can be administered alone or can be co-administered to the subject. Co-administration is meant to include simultaneous or sequential

administration of the compounds individually or in combination (more than one compound). The preparations can also be combined, when desired, with other active substances (e.g. antioxidants). For example, the compounds of the invention may be co-administered with glutathione, vitamin C, vitamin E, catalase, superoxide dismutase, glutathione peroxidase, various other peroxidases, and any other molecule or compound that is capable of scavenging reactive oxygen species known by those skilled in the art.

[0123] The substituted porphyrin compounds of the invention may be prepared and administered in a wide variety of oral, parenteral, and topical dosage forms. Thus, the compounds of the invention can be administered by injection (e.g. intravenously, intramuscularly, intracutaneously, subcutaneously, intraduodenally, or intraperitoneally). Also, the compounds described herein can be administered by inhalation, for example, intranasally. Additionally, the compounds of the invention can be administered transdermally. It is also envisioned that multiple routes of administration (e.g., intramuscular, oral, transdermal) can be used to administer the compounds of the invention. Accordingly, the invention also provides pharmaceutical compositions comprising a pharmaceutically acceptable carrier or excipient and one or more compounds of the invention.

[0124] For preparing pharmaceutical compositions from the compounds of the invention, pharmaceutically acceptable carriers can be either solid or liquid. Solid form preparations include powders, tablets, pills, capsules, cachets, suppositories, and dispersible granules. A solid carrier can be one or more substance that may also act as diluents, flavoring agents, binders, preservatives, tablet disintegrating agents, or an encapsulating material.

[0125] In powders, the carrier is a finely divided solid in a mixture with the finely divided active component. In tablets, the active component is mixed with the carrier having the necessary binding properties in suitable proportions and compacted in the shape and size desired.

[0126] The powders and tablets preferably contain from 5% to 70% of the active compound. Suitable carriers are magnesium carbonate, magnesium stearate, talc, sugar, lactose, pectin, dextrin, starch, gelatin, tragacanth, methylcellulose, sodium carboxymethylcellulose, a low melting wax, cocoa butter, and the like. The term "preparation" is intended to include the formulation of the active compound with encapsulating material as a carrier providing a capsule in which the active component with or without other carriers, is surrounded by a carrier, which is thus in association with it.

Similarly, cachets and lozenges are included. Tablets, powders, capsules, pills, cachets, and lozenges can be used as solid dosage forms suitable for oral administration.

[0127] For preparing suppositories, a low melting wax, such as a mixture of fatty acid glycerides or cocoa butter, is first melted and the active component is dispersed
5 homogeneously therein, as by stirring. The molten homogeneous mixture is then poured into convenient sized molds, allowed to cool, and thereby to solidify.

[0128] Liquid form preparations include solutions, suspensions, and emulsions, for example, water or water/propylene glycol solutions. For parenteral injection, liquid preparations can be formulated in solution in aqueous polyethylene glycol solution.

10 [0129] When parenteral application is needed or desired, particularly suitable admixtures for the compounds of the invention are injectable, sterile solutions, preferably oily or aqueous solutions, as well as suspensions, emulsions, or implants, including suppositories. In particular, carriers for parenteral administration include aqueous solutions of dextrose, saline, pure water, ethanol, glycerol, propylene glycol, peanut oil, sesame oil, polyoxyethylene-block
15 polymers, and the like. Ampoules are convenient unit dosages. The compounds of the invention can also be incorporated into liposomes or administered via transdermal pumps or patches. Pharmaceutical admixtures suitable for use in the invention include those described, for example, in *Pharmaceutical Sciences* (17th Ed., Mack Pub. Co., Easton, PA) and WO 96/05309, the disclosures of both of which are hereby incorporated by reference.

20 [0130] Aqueous solutions suitable for oral use can be prepared by dissolving the active component in water and adding suitable colorants, flavors, stabilizers, and thickening agents as desired. Aqueous suspensions suitable for oral use can be made by dispersing the finely divided active component in water with viscous material, such as natural or synthetic gums, resins, methylcellulose, sodium carboxymethylcellulose, and other well-known suspending
25 agents.

[0131] Also included are solid form preparations that are intended to be converted, shortly before use, to liquid form preparations for oral administration. Such liquid forms include solutions, suspensions, and emulsions. These preparations may contain, in addition to the active component, colorants, flavors, stabilizers, buffers, artificial and natural sweeteners,
30 dispersants, thickeners, solubilizing agents, and the like.

Dosages

[0132] The pharmaceutical preparation is preferably in unit dosage form. In such form the preparation is subdivided into unit doses containing appropriate quantities of the active component. The unit dosage form can be a packaged preparation, the package containing discrete quantities of preparation, such as packeted tablets, capsules, and powders in vials or ampoules. Also, the unit dosage form can be a capsule, tablet, cachet, or lozenge itself, or it can be the appropriate number of any of these in packaged form.

[0133] The quantity of active component in a unit dose preparation may be varied or adjusted from 0.1 mg to 10000 mg, more typically 1.0 mg to 1000 mg, most typically 10 mg to 500 mg, according to the particular application and the potency of the active component. The composition can, if desired, also contain other compatible therapeutic agents.

[0134] Some compounds may have limited solubility in water and therefore may require a surfactant or other appropriate co-solvent in the composition. Such co-solvents include: Polysorbate 20, 60, and 80; Pluronic F-68, F-84, and P-103; cyclodextrin; and polyoxyl 35 castor oil. Such co-solvents are typically employed at a level between about 0.01 % and about 2% by weight.

[0135] Viscosity greater than that of simple aqueous solutions may be desirable to decrease variability in dispensing the formulations, to decrease physical separation of components of a suspension or emulsion of formulation, and/or otherwise to improve the formulation. Such viscosity building agents include, for example, polyvinyl alcohol, polyvinyl pyrrolidone, methyl cellulose, hydroxy propyl methylcellulose, hydroxyethyl cellulose, carboxymethyl cellulose, hydroxy propyl cellulose, chondroitin sulfate and salts thereof, hyaluronic acid and salts thereof, and combinations of the foregoing. Such agents are typically employed at a level between about 0.01% and about 2% by weight.

[0136] The compositions of the invention may additionally include components to provide sustained release and/or comfort. Such components include high molecular weight, anionic mucomimetic polymers, gelling polysaccharides, and finely-divided drug carrier substrates. These components are discussed in greater detail in U.S. Pat. Nos. 4,911,920; 5,403,841; 5,212,162; and 4,861,760. The entire contents of these patents are incorporated herein by reference in their entirety for all purposes.

[0137] The dosage of the composition of the invention to be administered can be determined without undue experimentation and will be dependent upon various factors including the nature of the active agent (whether metal bound or metal free), the route of

administration, the subject, and the result sought to be achieved. A suitable dosage of the compound to be administered IV or topically can be expected to be in the range of about 0.01 to about 50 mg/kg/day, and more particularly, in the range of about 0.1 mg/kg/day to about 10 mg/kg/day. For aerosol administration, it is expected that the dose will be in the range of about 0.001 mg/kg/day to about 5 mg/kg/day, and more specifically, in the range of about 0.01 mg/kg/day to about 1 mg/kg/day. Suitable doses of the compounds will vary, for example, with the compound and with the result sought.

[0138] In certain embodiments, the compounds of the invention may be administered prophylactically to serve as a protectant against exposure to an alkylating agent. The compounds may be administered in the dosage amounts specified above about 1 hour to about 48 hours prior to alkylating agent exposure. In specific embodiments, the compound of the invention may be administered about 1 to about 24 hours, more specifically, about 1 to about 12 hours, more specifically about 1 to about 6 hours, and even more specifically, about 1 to about 6 hours prior to alkylating agent exposure.

[0139] In further embodiments, the compound of the invention may be administered in the dosage amounts specified above about 1 to about 48 hours following exposure to an alkylating agent. In specific embodiments, the compound of the invention may be administered about 1 to about 24 hours, more specifically, about 1 to about 12 hours, more specifically about 1 to about 6 hours, and even more specifically, about 1 to about 6 hours following alkylating agent exposure.

[0140] For any compound described herein, the therapeutically effective amount can be initially determined from cell culture assays. Target concentrations will be those concentrations of active compound(s) that are capable of counteracting the effects of the alkylating agent, by monitoring the presence, absence, or alteration in levels of the biomarkers indicative of alkylating agent exposure, such as glutathione, LDH, IgM, and 8O-HdG, for example. Methods for measuring the levels of such compounds is known by those of skill in the art and is matter of routine experimentation.

[0141] Therapeutically effective amounts for use in humans may be determined from animal models. For example, a dose for humans can be formulated to achieve a concentration that has been found to be effective in animals. The dosage in humans can be adjusted by monitoring the levels of the biomarkers indicative of exposure to an alkylating agent and adjusting the dosage upwards or downwards.

[0142] Dosages may be varied depending upon the requirements of the patient and the compound being employed. The dose administered to a patient, in the context of the invention, should be sufficient to effect a beneficial therapeutic response in the patient over time. The size of the dose also will be determined by the existence, nature, and extent of any adverse side effects. Generally, treatment is initiated with smaller dosages, which are less than the optimum dose of the compound. Thereafter, the dosage is increased by small increments until the optimum effect under circumstances is reached.

[0143] Dosage amounts and intervals can be adjusted individually to provide levels of the administered compound effective for the particular indication being treated. This will provide a therapeutic regimen that is commensurate with the severity of the individual's reaction following exposure to the alkylating agent.

[0144] Utilizing the teachings provided herein, an effective prophylactic or therapeutic treatment regimen can be planned that does not cause substantial toxicity and yet is entirely effective to treat the clinical symptoms demonstrated by the particular patient. This planning should involve the careful choice of active compound by considering factors such as compound potency, relative bioavailability, patient body weight, presence and severity of adverse side effects, preferred mode of administration, and the toxicity profile of the selected agent.

[0145] Without further elaboration, it is believed that one skilled in the art using the preceding description can utilize the invention to the fullest extent. The following examples are illustrative only, and not limiting of the disclosure in any way whatsoever.

EXAMPLES

[0146] For the purpose of the following specific examples, the compounds of Formulas III-IX described in the detailed description above, will be designated as indicated in Table 1, immediately below:

Table 1

Compound of Formula	AEOL No. Designation
IV	AEOL 10153
V	AEOL 10158
VI	AEOL 10123

VII	AEOL 10150
VIII	AEOL 10151
IX	AEOL 10303
X	AEOL 10113

Specific Example 1: CEES-Induced Airway Epithelial Cell Injury

[0147] Human lung 16HBE cells were grown to approximately 90% confluence and treated with increasing concentrations of CEES, ranging from about 600 to about 000 μ M. Cell viability was determined by measuring the fluorescence of calcein AM and was found to decrease in a dose-dependent manner from 80% with the 600 μ M CEES to below 10% with 1000 μ M CEES (Figure 2). 900 μ M CEES was used as the optimal dose to carry out the cytoprotection studies because it provided enough cell injury (about 50%) for potential therapeutics to demonstrate efficacy and the most consistent cell injury response in the two cell systems. Because of observed increased resistance of SAE cells to CEES toxicity as seen with 16HBE cells, these exposures were prolonged to 48 h in the SAE cells to provide similar injury responses for comparison of antioxidant protective effects between cell systems.

Specific Example 2: Delayed Increase in Mitochondrial ROS and Dysfunction with CEES Exposure

[0148] As discussed above, mitochondria are a major source of cellular ROS production. Both SAE and 16HBE cells were exposed to 900 μ M CEES for 2, 4, 6, 8, 12, 24, and 48 h, after which the cells were incubated with MitoSOX (MitoSOX is a mitochondrially targeted ROS probe) and fluorescence was measured using flow cytometry. CEES exposure increased ROS levels that peaked at 12 h, and this time-dependent increase was seen in both SAE (Figure 3A) and 16HBE (Figure 3B) cells. As a consequence, further exposure studies measuring markers of cellular stress were examined after 12 h of exposure.

[0149] Next CEES was examined to determine whether CEES exposure was associated with any mitochondrial dysfunction. Mitochondria need to maintain a membrane potential to actively make ATP. To examine this, measured Rho 123 fluorescence was measured, which is inversely correlated with mitochondrial membrane potential. Human lung 16HBE cells were exposed to CEES for 2, 4, 6, 8, 12, 24, and 48 h, after which the cells were incubated with Rho 123, and fluorescence was measured using flow cytometry. The results showed that

CEES produced a decrease in mitochondrial membrane potential by 4 h, which persisted for 24 h as evidenced by the increase in Rho 123 fluorescence (**Figure 3C**). Notably, there was a significant decrease in Rho 123 fluorescence at 48 h, which can be attributed to the cell death that would be expected to occur based on previous cell viability tests.

5 Specific Example 3: Metalloporphyrins Rescue Human Lung Cells from CEES-Induced Toxicity

[0150] Several structurally different metalloporphyrins (AEOL 10150, AEOL 10113, AEOL 10303, and MnTBAP) were screened in 16HBE cells for efficacy against CEES toxicity 1 h after the initial exposure (**Figure 4**). Cells were treated with CEES for 1 h at
10 37°C, after which the compounds of Formula 10150 (Formula VI, above), 10113 (Formula IX, above), 10103 (Formula VIII, above) and MnTBAP were added at a final concentration of 50 μ M. After 24 h, cell viability was measured using calcein AM fluorescence. Three catalytic antioxidant compounds significantly increased cell viability in CEES-exposed cells to 60, 56, and 41% in the 10150, 10113, 10103 groups compared with only 20% in CEES-
15 only exposed cells (**Figure 5**). Of the four compounds tested, only MnTBAP did not show any protection.

Specific Example 4: AEOL 10150 Rescues Human Primary Airway Cells from CEES-Induced Toxicity

[0151] Primary human lung SAE cells and 16HBE cells were exposed to 900 μ M CEES for
20 48 h. Treatment with AEOL 10150 (10, 25, and 50 μ M) occurred 1 h after the initial CEES exposure. AEOL 10150 (50 μ M) alone did not change the viability of the cells, as measured by both the calcein AM (**Figure 6, A and C**) and the MTT (**Figure 6, B and D**) assays. CEES alone resulted in a 50% decrease in cell viability, and this was significantly attenuated at the highest concentration of AEOL 10150, to 80% of the control in SAE cells (**Figure 6, A
25 and B**) and nearly 90% in 16HBE cells (**Figure 6, C and D**). Although neither 10 nor 25 μ M AEOL 10150 showed a significant increase in viability in the SAE cells, 25 μ M AEOL 10150 did show a significant increase in viability in the 16HBE cells. Similar results were obtained in both the calcein AM and the MTT assays used to assess cell viability.

30 Specific Example 5: AEOL 10150 Prevents CEES-Mediated Mitochondrial ROS and Dysfunction

[0152] AEOL 10150 were assessed to determine whether its cytoprotective effects are associated with CEES-mediated changes in mitochondrial ROS and dysfunction. Cells were grown to approximately 90% confluence and exposed to 900 μ M CEES with and without

AEOL 10150 (50 μ M). Cells were incubated with MitoSOX 12 h after CEES exposure, and fluorescence was measured using flow cytometry. AEOL 10150 added 1 h after CEES treatments significantly decreased mitochondrial ROS compared with CEES exposed cells in both SAE (**Figure 7A**) and 16HBE (**Figure 7B**) cells. AEOL 10150 alone did not cause a change in mitochondrial ROS.

[0153] Additionally, AEOL 10150 was assessed to determine if it can protect the mitochondria from CEES-induced dysfunction. Lung 16HBE cells were exposed to 900 μ M CEES for 4 h with 50 μ M AEOL 10150 added 1 h after the initial CEES exposure. The CEES-only treated groups showed an increase in Rhodamine 123 fluorescence, indicating a significant loss of mitochondrial membrane potential that was attenuated in the AEOL 10150-treated cells (**Figure 7C**).

Specific Example 6: AEOL 10150 Prevents CEES-Induced Oxidative Stress

[0154] Oxidative stress can result from an imbalance between oxidant production and antioxidant defense. As discussed above, GSH is a major cellular antioxidant. So, the effect of CEES on total cellular GSH levels was determined as well as whether AEOL 10150 altered CEES-mediated changes in GSH levels. Human lung 16HBE cells were exposed for 12 h to CEES, and AEOL 10150 (50 μ M) was added 1 h post-CEES treatment. AEOL 10150 alone did not alter intracellular GSH levels, whereas CEES caused a significant decrease in intracellular GSH levels (**Figure 8A** AEOL 10150 treatment prevented the CEES-induced decrease in GSH, further implicating an imbalance in redox status of the cells caused by CEES that was reversible by AEOL 10150).

[0155] One consequence of oxidative stress is an increase in the oxidation of cellular macromolecules. A classic marker for DNA oxidation is the formation of 8-hydroxydeoxyguanosine (8O-HdG), which was determined 12 h after CEES exposure. CEES caused a significant increase in 8OHdG levels in lung 16HBE cells as measured by high-performance liquid chromatography (**Figure 8B**). Moreover, AEOL 10150 added 1 h post-CEES exposure decreased CEES-mediated DNA oxidation. These data further support the role of oxidative stress in CEES-mediated injury that is ameliorated by the catalytic antioxidant metalloporphyrin, AEOL 10150.

Specific Example 7: AEOL 10150 Protects CEES-Induced Lung Injury in Rat

[0156] Rats were exposed to 5% CEES for 15 minutes and killed 18 hours later. Groups of rats received AEOL 10150 (5 mg/kg sc, bid) 1 hour after CEES exposure. Rat lungs were

lavaged and markers of cytotoxicity, inflammation and edema were measured in bronchoalveolar lavage fluid (BALF). As shown in **Figure 9**, CEES caused a significant increase in the ROS. Moreover, AEOL 10150 added 1 h post-CEES exposure decreased CEES-mediated DNA oxidation. These data further support the role of oxidative stress in CEES-mediated injury that is ameliorated by the catalytic antioxidant metalloporphyrin, AEOL 10150.

Specific Example 8: AEOL 10150 Reduces CEES-induced Cytotoxicity as Measured by LDH Release

[0157] CEES-induced cytotoxicity may be assessed by measuring LDH release in the lung. LDH release in the bronchoalveolar lavage fluid (BAL) is a marker of cellular injury in the epithelium. **Figure 10** shows levels of LDH release were not different between EtOH + PBS and EtOH + AEOL 10150 treated animals. Following CEES exposure with PBS treatment, LDH release doubled as compared to the control groups ($p < 0.01$). When rats were administered AEOL 10150 following CEES-exposure, LDH levels were significantly attenuated as compared to the CEES + PBS group ($p < 0.001$).

Specific Example 9: AEOL 10150 Reduces CEES-induced BAL Increases in Protein and IgM

[0158] Administering AEOL 10150 reduces alkylating agent-induced increases in protein and IgM in the lung. BAL in normal rats consists of macrophages and low levels of large proteins such as albumin. Measuring protein levels in the BAL is one way to measure the accumulation of extravascular protein in the airways. As shown in **Figure 11A**, compared to EtOH + PBS or EtOH + AEOL 10150, protein levels in BAL were significantly increased as a result of 5% CEES + PBS ($p < 0.001$). Protein levels in the BAL were significantly decreased from CEES + PBS when animals were administered AEOL 10150 ($p < 0.001$). Although increased protein levels in BAL may not be a clear indicator of vascular permeability because it may also indicate lysis of damaged epithelium resulting from CEES exposure, the presence of very high molecular weight molecules such as IgM (900 kD) are clearly indicative of increased vascular permeability. Accordingly, **Figure 11B** demonstrates that IgM levels in the BAL were significantly increased a result in CEES + PBS rats as compared to EtOH + PBS or EtOH + AEOL 10150 ($p < 0.001$). IgM levels were significantly decreased with CEES + AEOL 10150 treatment as compared to CEES + PBS. Combined, these data demonstrate that administration of the AEOL 10150 following CEES exposure decreased protein levels in BAL as well as IgM levels.

Specific Example 10: AEOL 10150 Treatment Reduces Levels of RBCs and Inflammatory Cells in BAL

[0159] Administering AEOL 10150 following alkylating agent exposure reduces levels of red blood cells (RBCs) and inflammatory cells in the lung. RBCs should not be present in the lung in any considerable levels unless there is hemorrhagic injury. Exposure to 5% CEES + PBS results in significantly increased hemorrhage as shown by increased RBC levels in the BAL ($p < 0.001$). This CEES-induced damage is ameliorated with AEOL 10150 treatment 18 hours after CEES exposure ($p < 0.05$). Levels of PMN or neutrophils in the BAL were significantly increased in the CEES + PBS rats as compared to EtOH + PBS or EtOH+10150 ($p < 0.001$). CEES-induced neutrophil increases were significantly decreased with AEOL 10150 treatment ($p < 0.05$). While there was a decrease in macrophage levels with CEES exposure, this change did not reach significance as compared to the EtOH exposed animals.

Specific Example 11: Myeloperoxidase (MPO) in Lung Homogenate.

[0160] MPO is a glycoprotein expressed in all cells of the myeloid lineage but is most abundant in the azurophilic granules of PMNs. Released MPO by activated PMNs measured in whole lung homogenate demonstrates tissue accumulation and is a useful complement to measurement of PMN in the BAL. MPO levels were significantly increased as a result of CEES+PBS indicating an increase in PMN tissue accumulation ($p < 0.01$, **Figure 12**). AEOL 10150 treatment after CEES treatment significantly decreased tissue accumulation of PMN ($p < 0.05$).

Specific Example 12: AEOL 10150 Prevents CEES-induced Oxidative Stress

[0161] Oxidative stress occurs when oxidant production exceeds antioxidant defense. One marker of oxidative damage is DNA oxidation, which can be measured by the formation of 8-hydroxy-2-deoxyguanosine (8OHdG). 8OHdG significantly increased in CEES+PBS rats as compared to levels in EtOH+PBS ($p < 0.01$) or EtOH+ 10150 ($p < 0.05$) treatment 18 hours after exposure as measured by HPLC (**Figure 13**). When rats were exposed to CEES and then received AEOL 10150, 8O-HdG levels were significantly decreased as compared to CEES+PBS ($p < 0.05$). These data further support the role of oxidative stress in CEES-mediated injury that is ameliorated by the catalytic antioxidant metalloporphyrin, AEOL 10150.

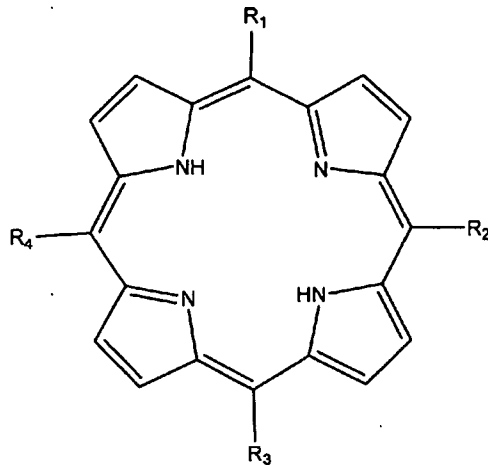
[0162] Another marker of oxidative damage is the formation of lipid peroxidation products including 4-hydroxynonenal (4-HNE). 4-HNE is a major product of total unsaturated

aldehydes formed during lipid peroxidation. Measurement of 4-HNE levels in the lung 18 hours after CEES exposure resulted in a significant increase compared with EtOH+PBS treated rats (Figure 14). AEOL 10150 significantly inhibited CEES- induced lipid peroxidation.

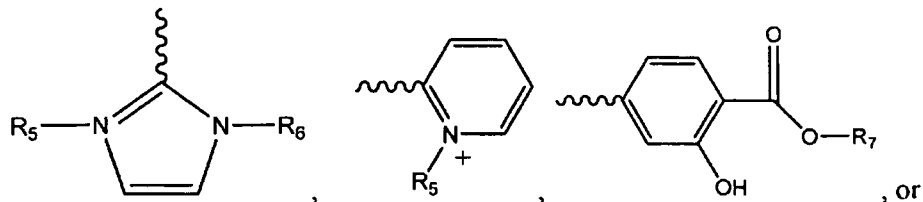
- 5 [0163] The examples given above are merely illustrative and are not meant to be an exhaustive list of all possible embodiments, applications or modifications of the invention. Thus, various modifications and variations of the described methods and systems of the invention will be apparent to those skilled in the art without departing from the scope and spirit of the invention. Although the invention has been described in connection with specific
- 10 embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiments. Indeed, various modifications of the described modes for carrying out the invention which are obvious to those skilled in cellular and molecular biology, chemistry, or in the relevant fields are intended to be within the scope of the appended claims.
- 15 [0164] The disclosures of all references and publications cited above are expressly incorporated by reference in their entireties to the same extent as if each were incorporated by reference individually.

WHAT IS CLAIMED IS:

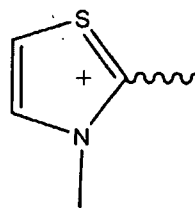
- 1 1. A method of treating an injury associated with exposure to an
 2 alkylating agent in a subject, said method comprising the step of:
 3 administering to a subject in need thereof an effective amount of a
 4 compound of formula



- 5
 6 or a pharmaceutically acceptable salt thereof,
 7 wherein R₁, R₂, R₃, and R₄ are each independently



- 8
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- 10
 11 wherein R₅, R₆, and R₇ are each independently selected from the group
 12 consisting of an unsubstituted or substituted alkyl, unsubstituted or substituted heteroalkyl,
 13 unsubstituted or substituted cycloalkyl, unsubstituted or substituted heterocycloalkyl,
 14 unsubstituted or substituted aryl, unsubstituted or substituted heteroaryl, halogen, -CN, -CF₃,
 15 -OH, -NH₂, and -COOH.

- 1 2. The method of claim 1, wherein the compound is bound to a metal.

1 3. The method of claim 2, wherein the metal is selected from the group
 2 consisting of manganese, iron, cobalt, copper, nickel, and zinc.

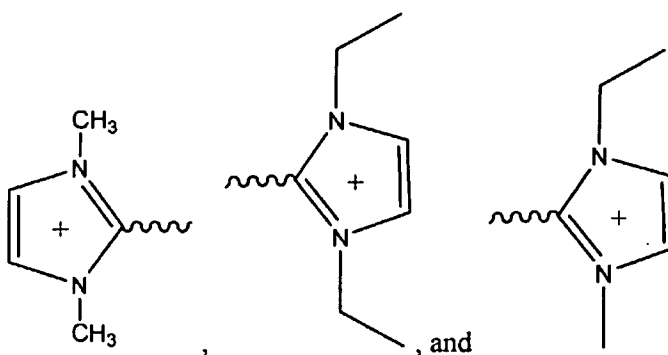
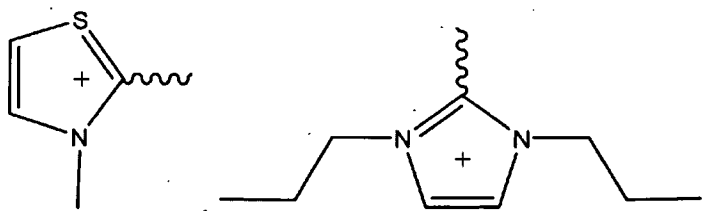
1 4. The method of claim 3, wherein the compound is bound to manganese.

1 5. The method of claim 1, wherein R₅, R₆, and R₇ are independently a
 2 substituted or unsubstituted C₁₋₂₀ alkyl.

1 6. The method of claim 5, wherein R₅, R₆, and R₇ are independently a
 2 substituted or unsubstituted C₁₋₁₀ alkyl.

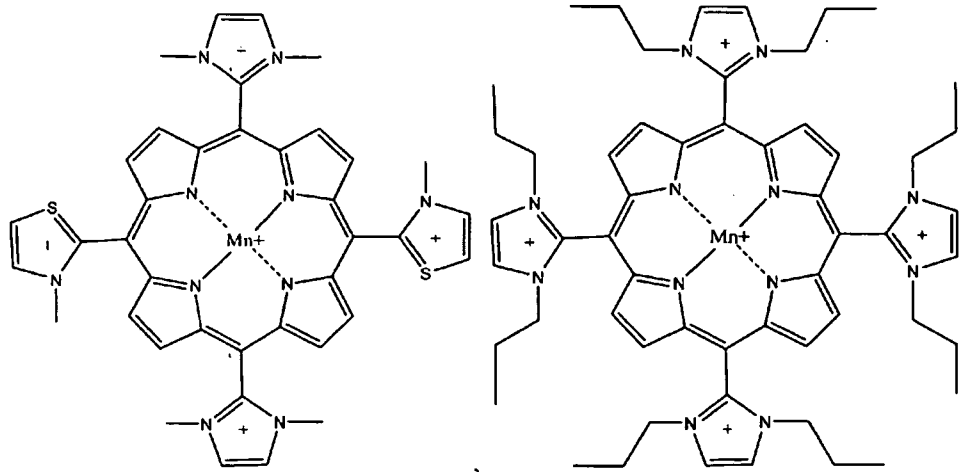
1 7. The method of claim 6, wherein R₅, R₆, and R₇ are independently
 2 selected from the group consisting of hydrogen, methyl, ethyl, and propyl.

1 8. The method of claim 7, wherein R₁, R₂, R₃, and R₄ are independently
 2 selected from the group consisting of



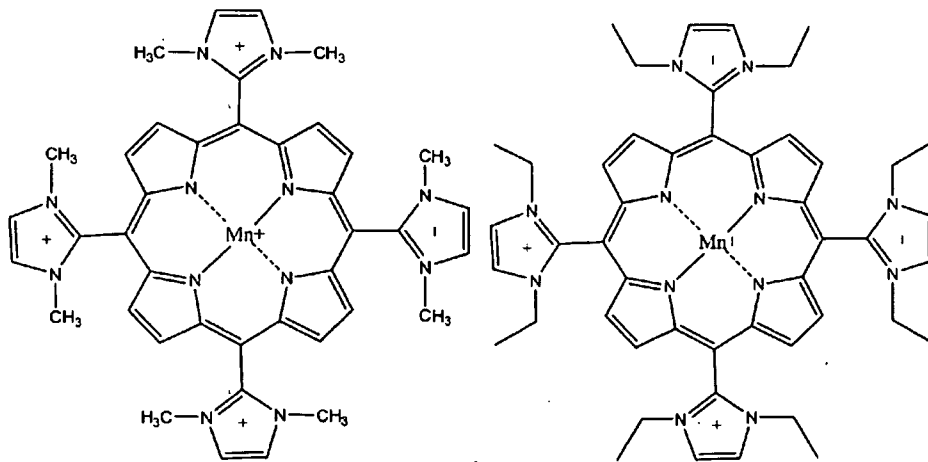
1 9. The method of claim 8, wherein the compound has a formula selected
 2 from the group consisting of

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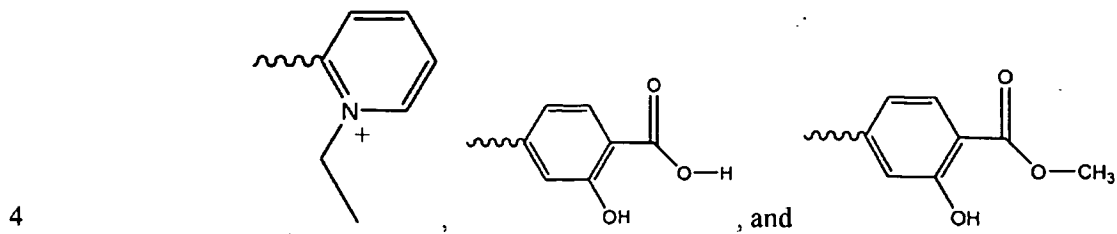


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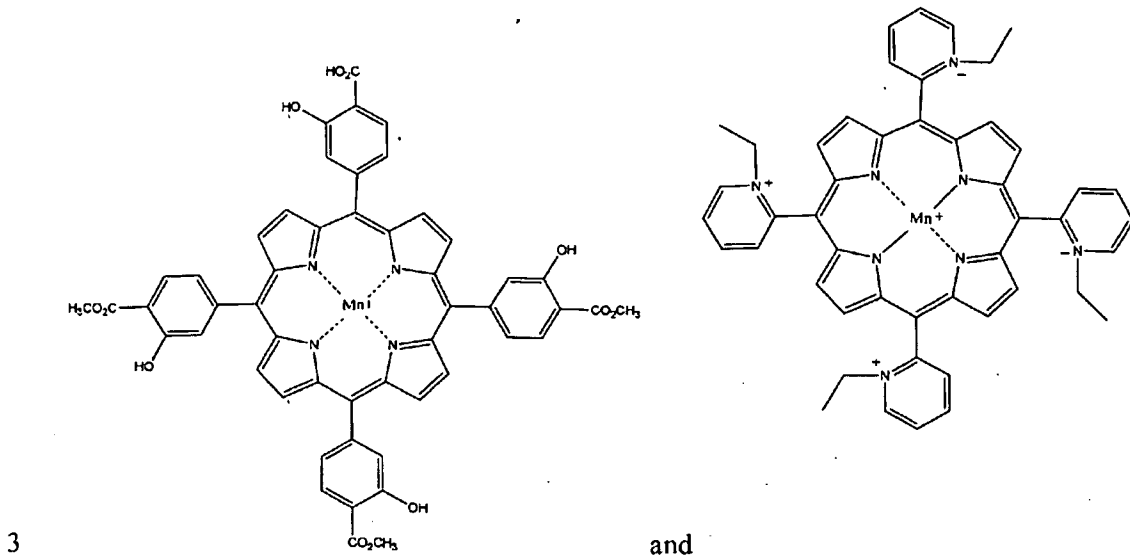
7 and

10. The method of claim 1, wherein R_1 , R_2 , R_3 , and R_4 are independently selected from the group consisting of

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1 11. The method of claim 10, wherein the compound has the formula
 2 selected from the group consisting of



1 12. The method of claim 1, wherein the injury is an injury to an organ in
 2 the subject.

1 13. The method of claim 12, wherein the organ is skin, lungs, nose,
 2 esophagus, trachea, or bronchi.

1 14. The method of claim 1, wherein the alkylating agent is selected from
 2 the group consisting of a sulfur mustard, chlorine gas, phosgene, and 2- chloroethyl ethyl
 3 sulfide.

1 15. The method of claim 14, wherein the alkylating agent is a sulfur
 2 mustard.

1 16. The method of claim 1, wherein said administration is selected from
 2 the group consisting of inhalation administration, topical administration, intravenous
 3 administration, subcutaneous administration, intraperitoneal administration, and intramuscular
 4 administration.

1 17. The method of claim 1, wherein exposure to the alkylating agent
2 produces mitochondrial dysfunction.

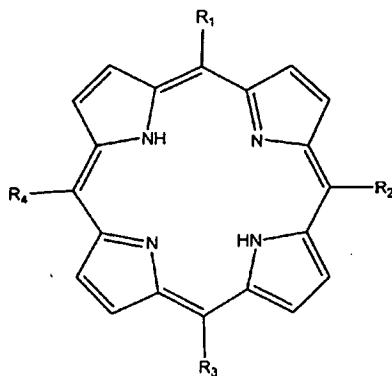
1 18. The method of claim 17, wherein the mitochondrial dysfunction causes
2 an increase in reactive oxygen species production or oxidative stress.

1 19. The method of claim 1, wherein the exposure to the alkylating agent
2 relative to non-exposure to the alkylating agent, causes an increase in lactate dehydrogenase
3 (LDH) levels, an increase in IgM levels, a decrease of glutathione levels, and an increase in
4 myleperoxidase levels.

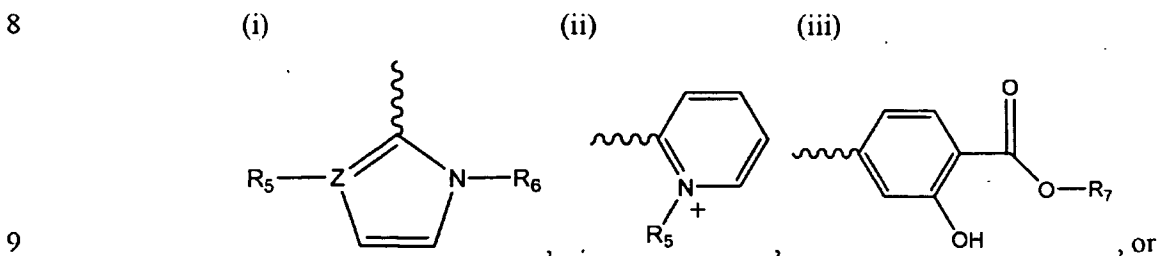
1 20. The method of claim 1, wherein the compound is administered to the
2 subject within about 0.5 hours to about 48 hours after exposure to the alkylating agent.

1 21. The method of claim 1, wherein the compound is administered to the
2 subject within about 1 hour to about 10 hours after exposure to the alkylating agent.

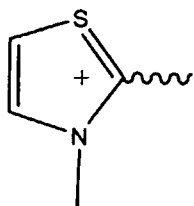
1 22. A method of protecting a subject from the toxic effects associated with
2 exposure to an alkylating agent, comprising the step of:
3 administering prophylactically to a subject in need thereof an effective amount
4 of a compound of formula



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6 or a pharmaceutically acceptable salt thereof,
7 wherein R₁, R₂, R₃, and R₄ are each independently



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wherein R₅, R₆, and R₇ are each independently selected from the group consisting of an unsubstituted or substituted alkyl, unsubstituted or substituted heteroalkyl, unsubstituted or substituted cycloalkyl, unsubstituted or substituted heterocycloalkyl, unsubstituted or substituted aryl, unsubstituted or substituted heteroaryl, halogen, -CN, -CF₃, -OH, -NH₂, and -COOH.

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23. The method of claim 22, wherein the compound is bound to a metal.

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24. The method of claim 23, wherein the metal is selected from the group consisting of manganese, iron, cobalt, copper, nickel, and zinc.

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25. The method of claim 24, wherein the compound is bound to manganese.

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26. The method of claim 22, wherein R₅, R₆, and R₇ are independently a substituted or unsubstituted C₁₋₂₀ alkyl.

1

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27. The method of claim 26, wherein R₅, R₆, and R₇ are independently a substituted or unsubstituted C₁₋₁₀ alkyl.

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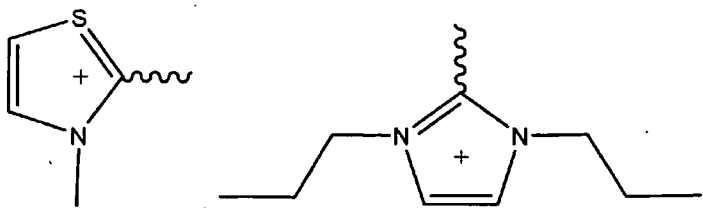
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28. The method of claim 27, wherein R₅, R₆, and R₇ are independently selected from the group consisting of hydrogen, methyl, ethyl, and propyl.

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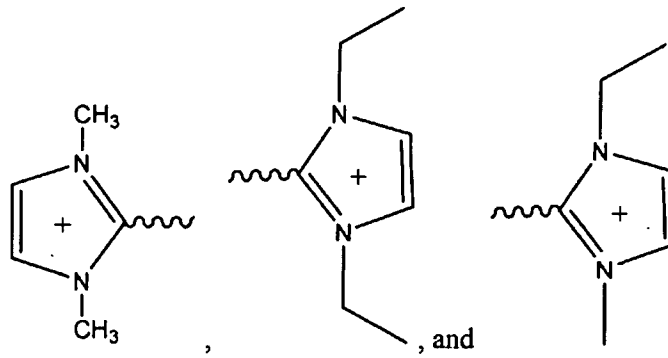
29. The method of claim 28, wherein R₁, R₂, R₃, and R₄ are independently selected from the group consisting of



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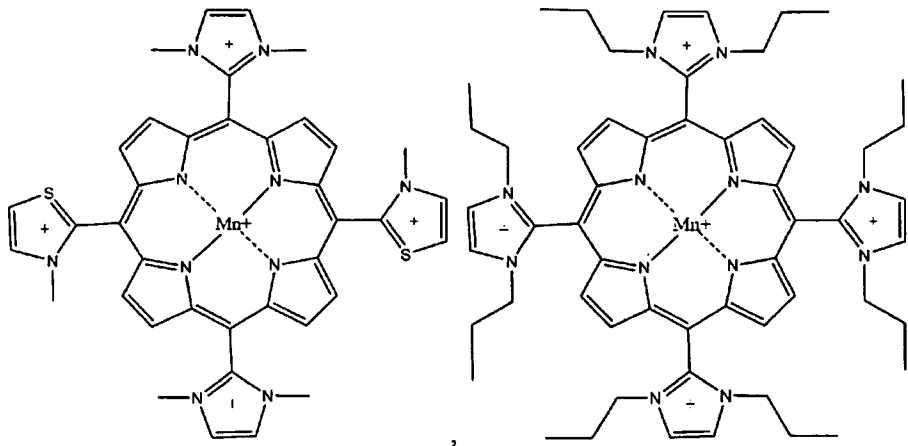
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30. The method of claim 29, wherein the compound has a formula selected

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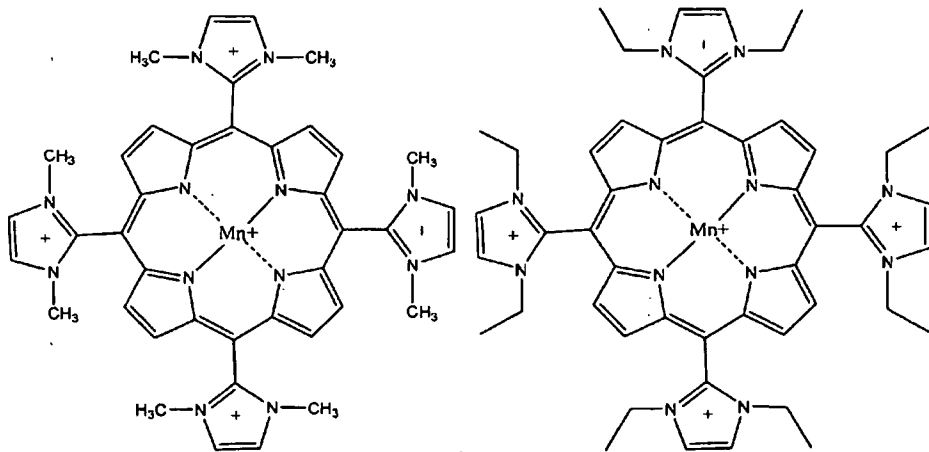
from the group consisting of

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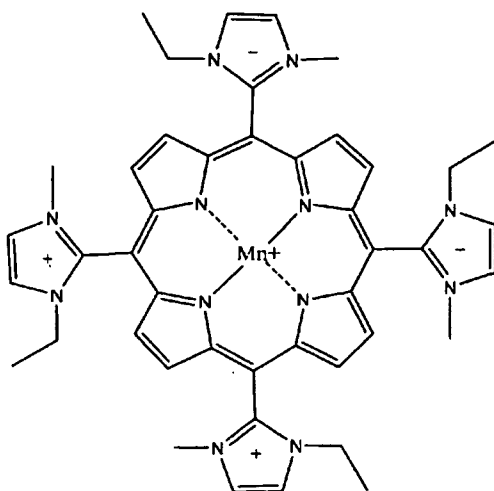
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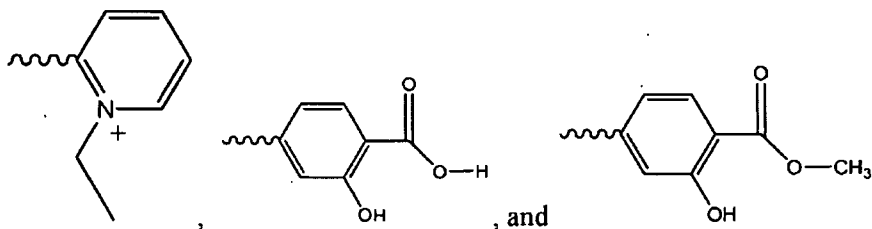
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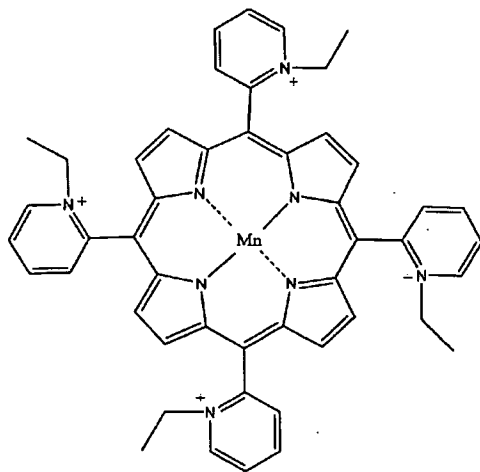
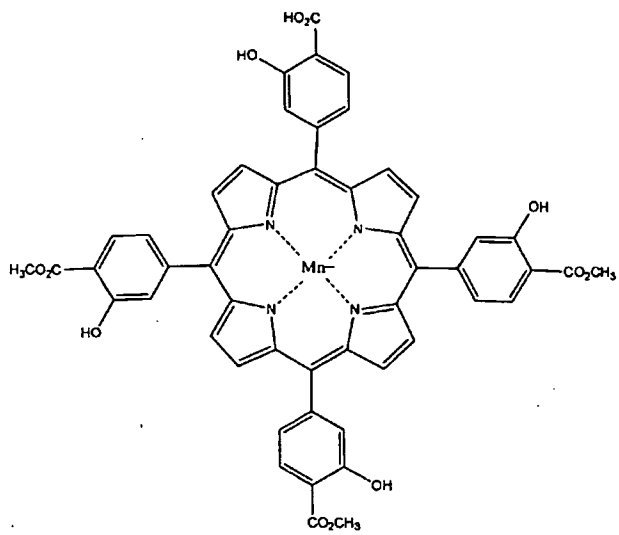
1 31. The method of claim 22, wherein R₁, R₂, R₃, and R₄ are each
 2 independently selected from the group consisting of

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1 32. The method of claim 31, wherein the compound has the formula
 2 selected from the group consisting of



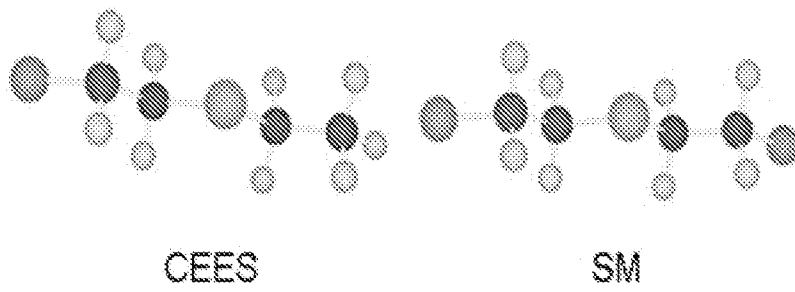


FIGURE 1

2 / 15

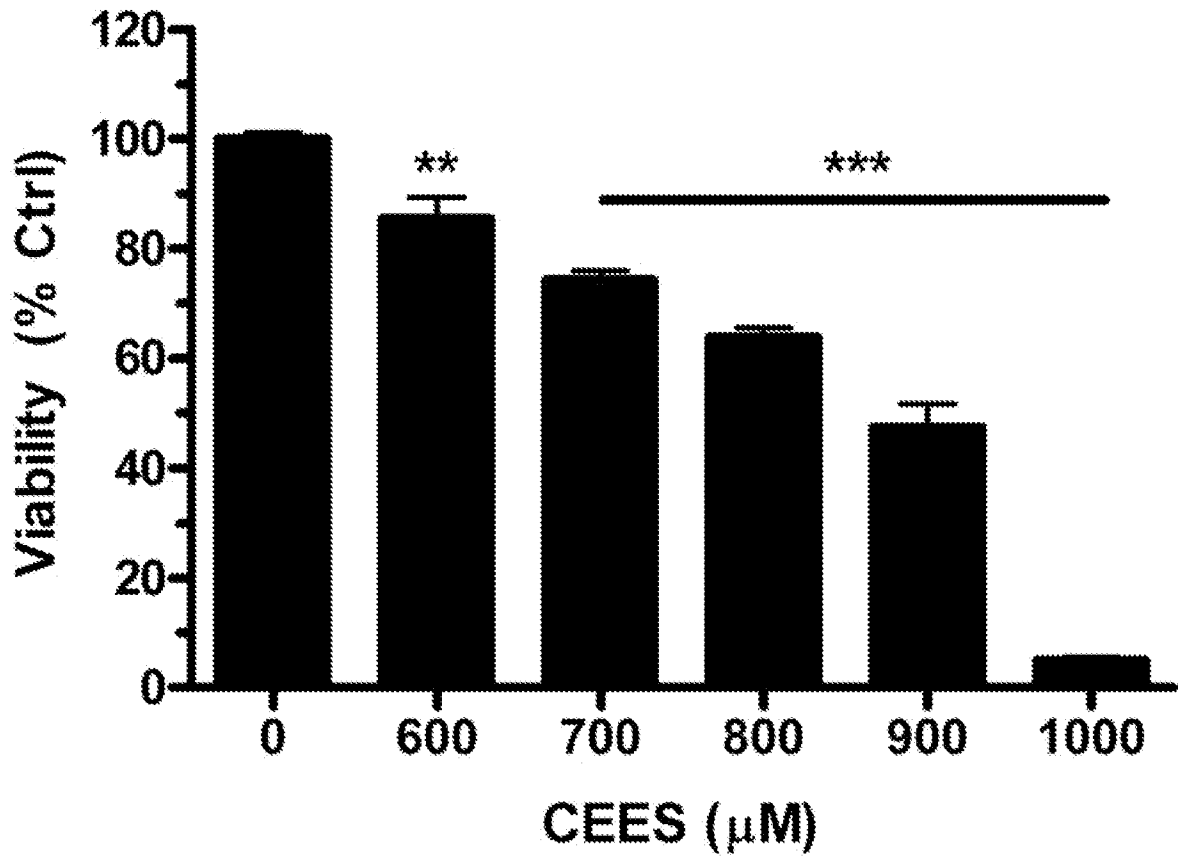
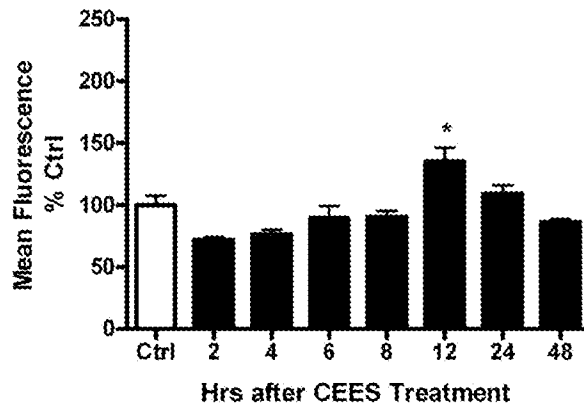


FIGURE 2

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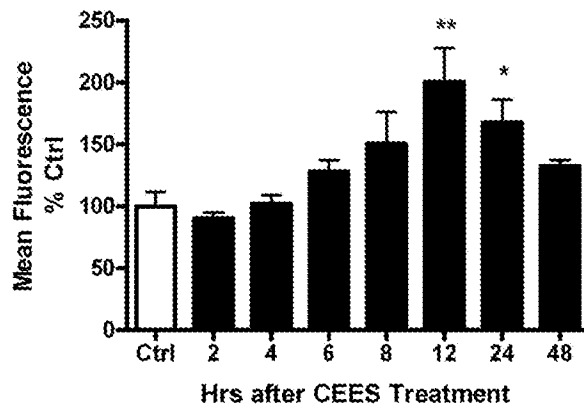
A

SAE Cells
MitoSOX



B

16HBE Cells
MitoSOX



C

16HBE Cells
Rhodamine 123

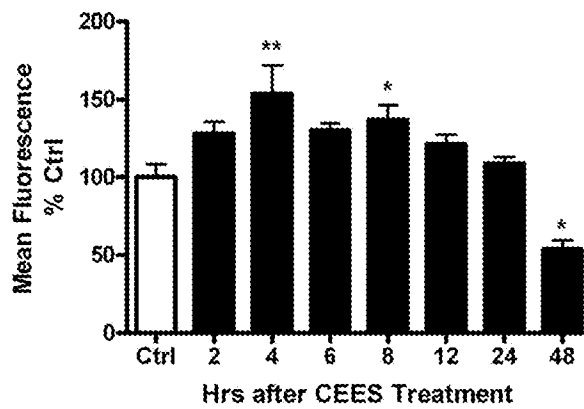
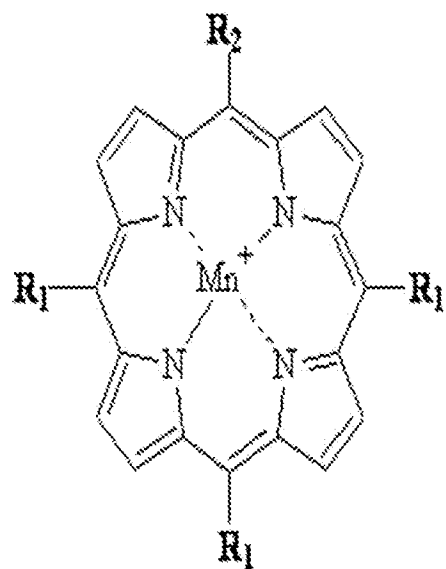


FIGURE 3

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R	Drug Code	Substitutions
	MnTBAP	(R ₁ & R ₂)
	AEOL 10303	(R ₂)
	AEOL-10113	(R ₁)
	AEOL-10113	(R ₁ & R ₂)
	AEOL-10150	(R ₁ & R ₂)

FIGURE 4

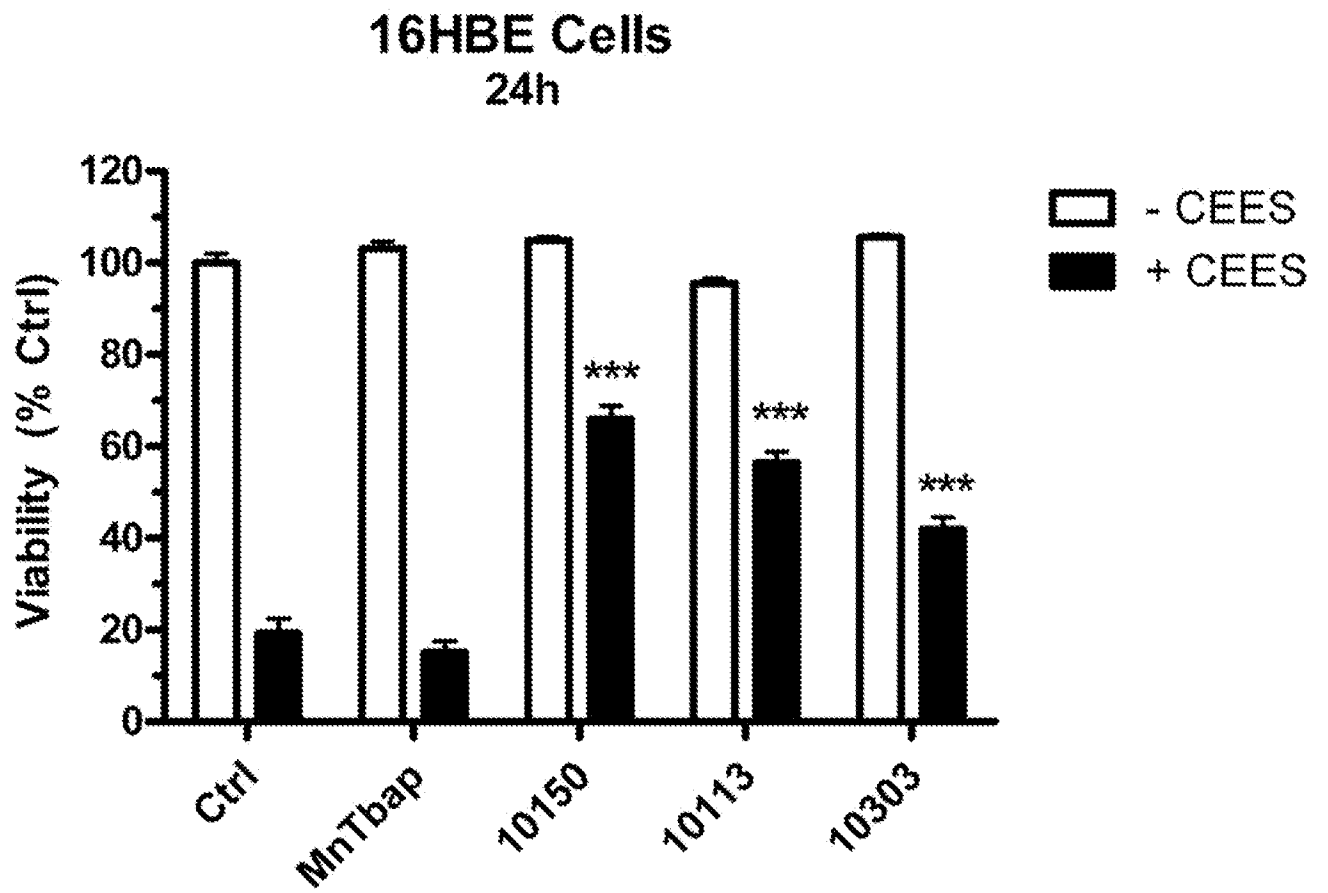


FIGURE 5

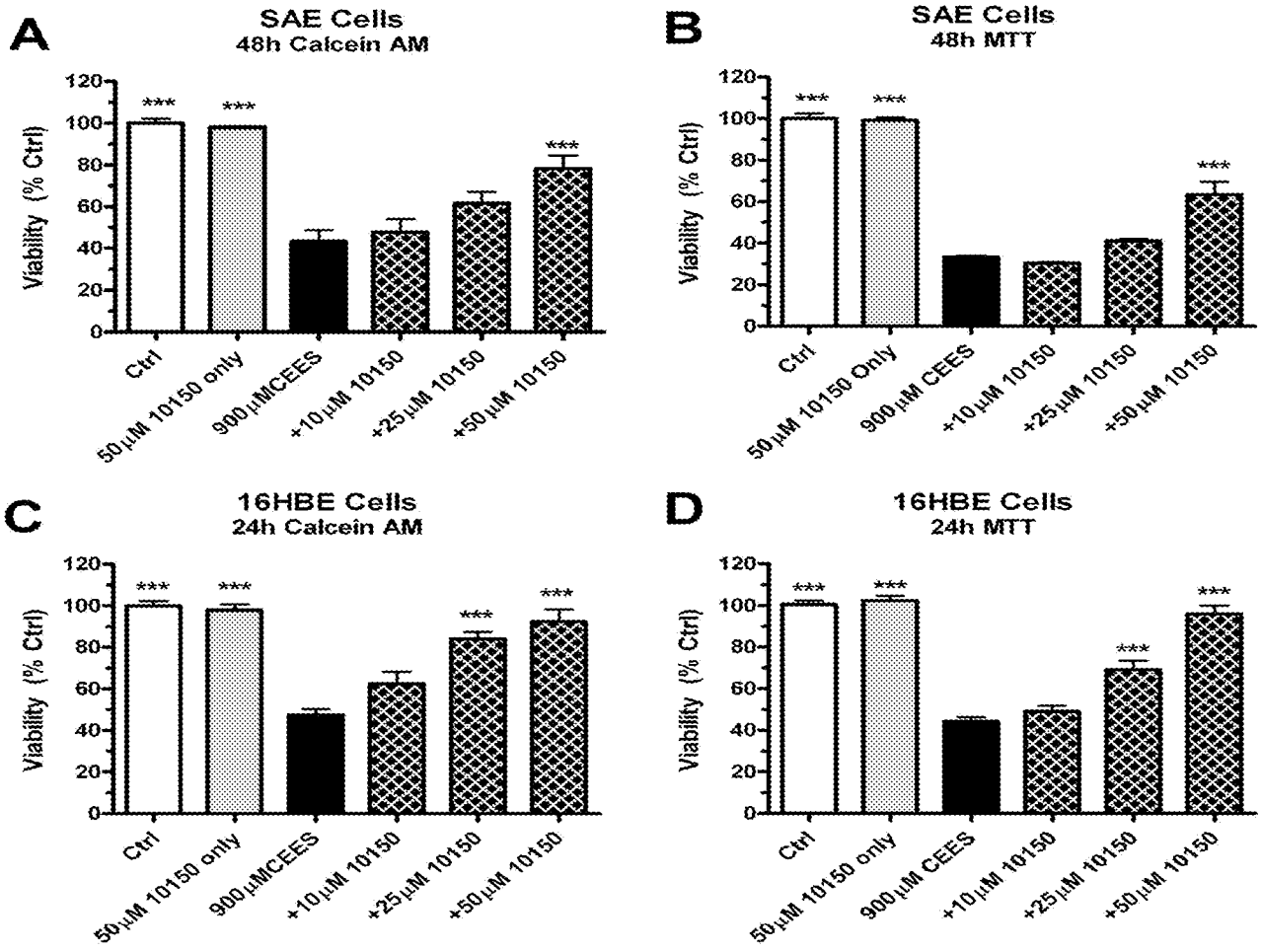
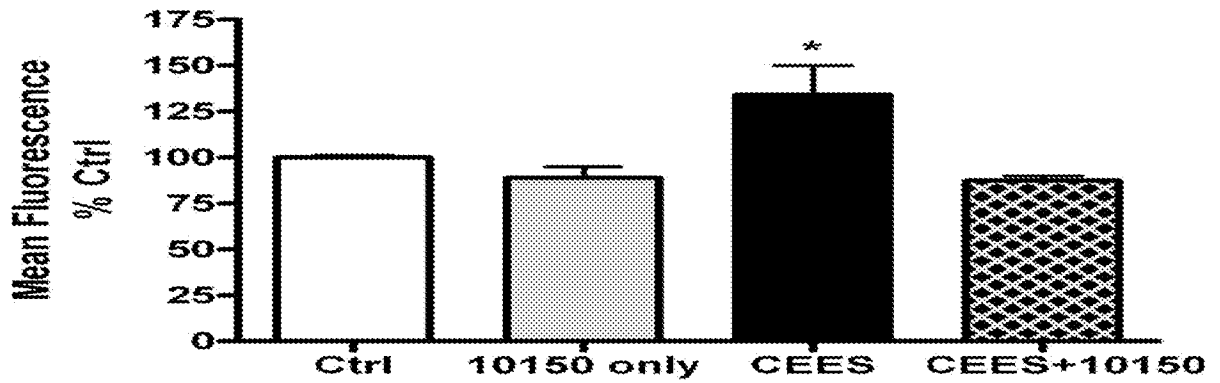


FIGURE 6

7 / 15

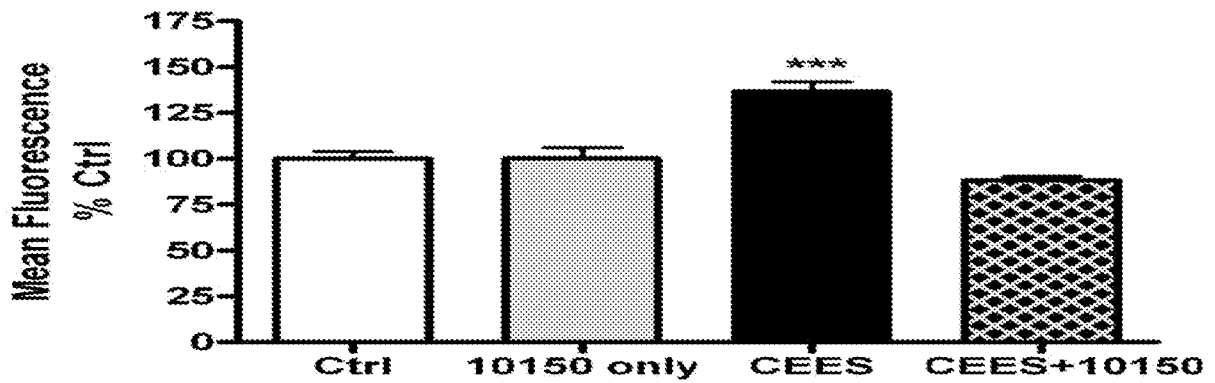
A

**SAE Cells
MitoSOX
12h**



B

**16HBE Cells
MitoSOX
12h**



C

**16HBE Cells
Rhodamine 123
4h**

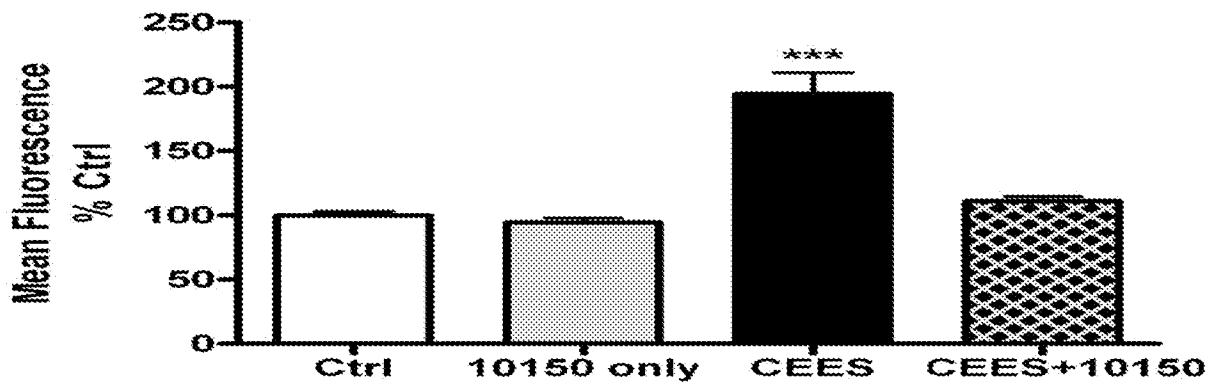


FIGURE 7

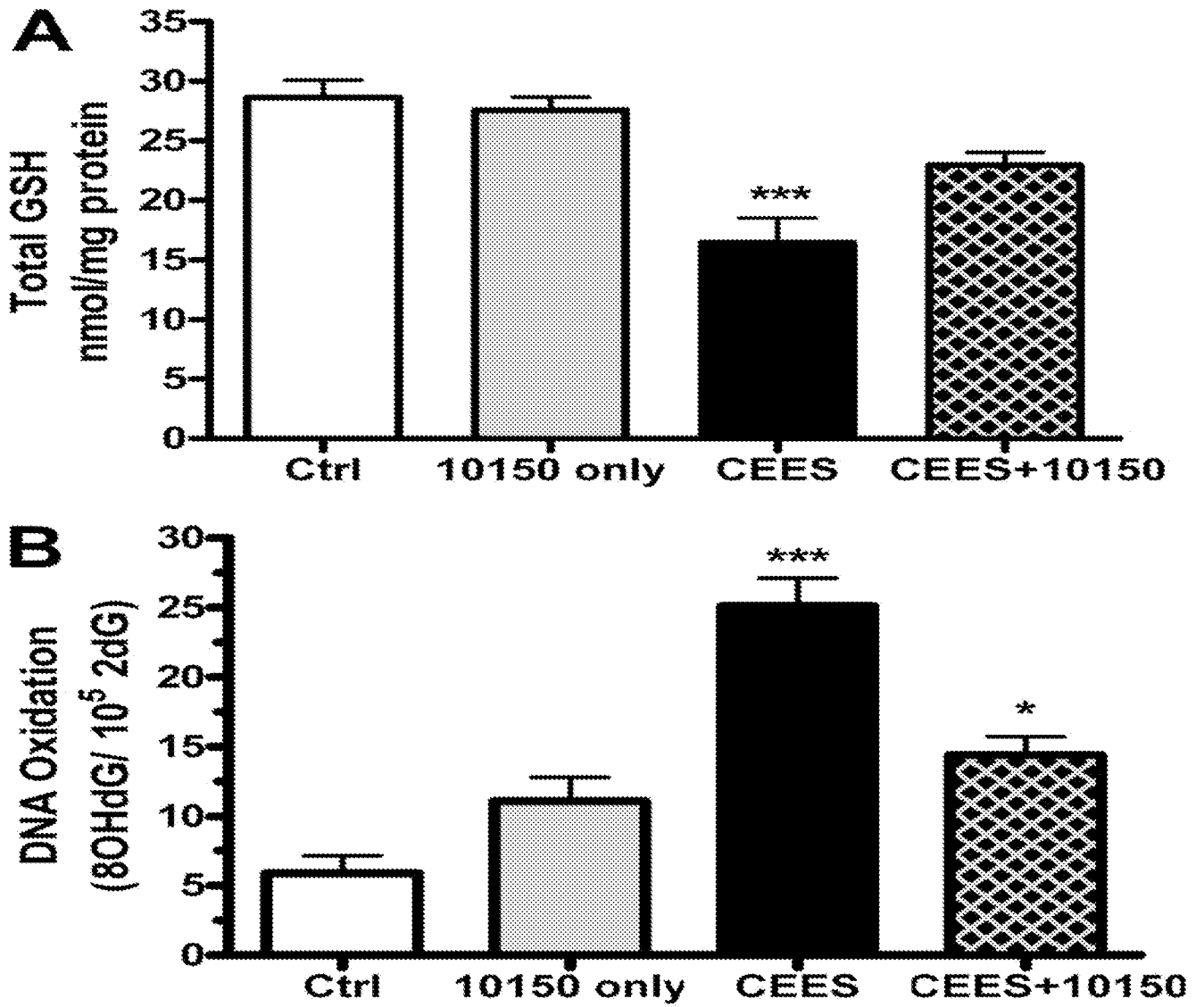


FIGURE 8

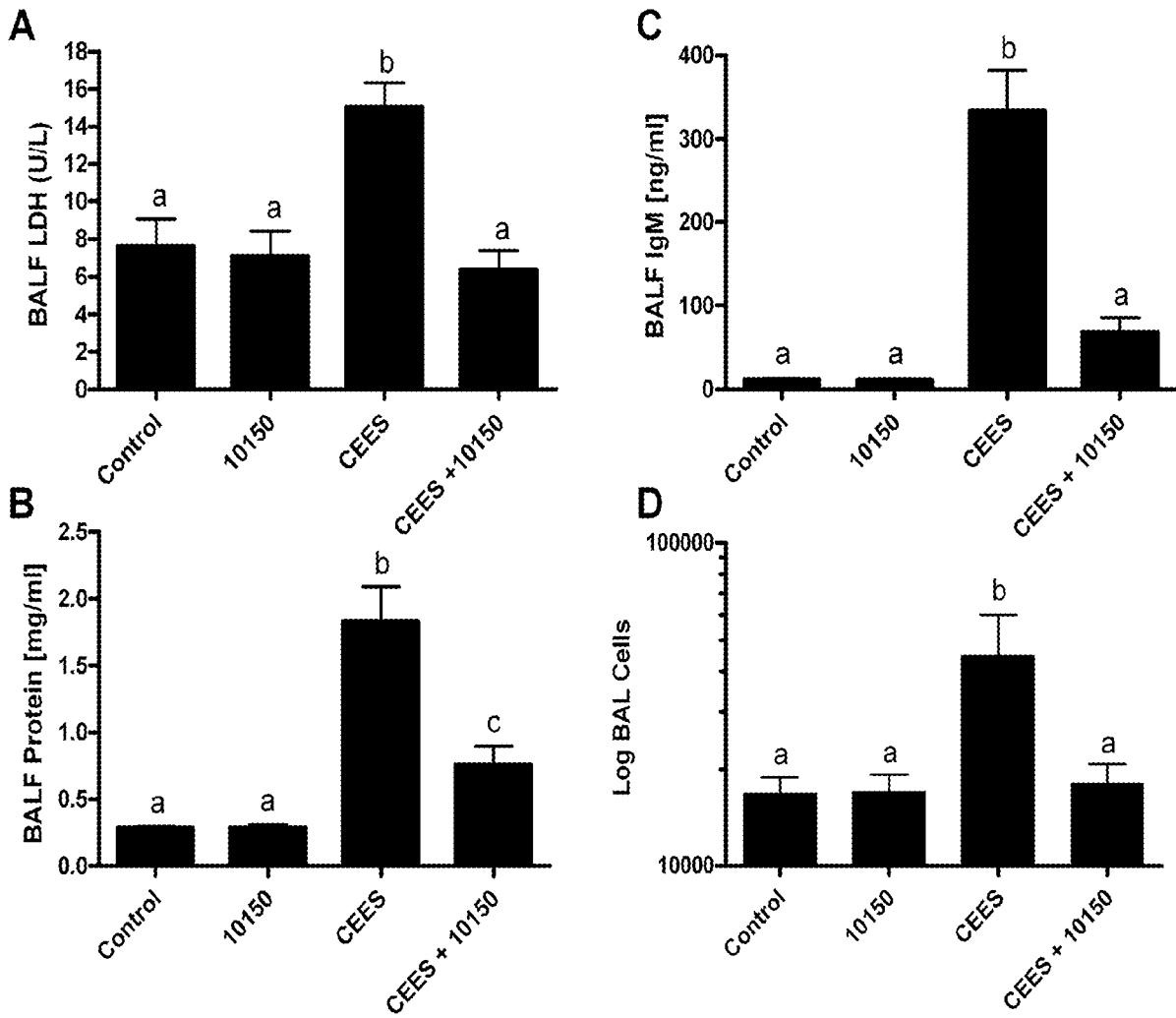


FIGURE 9

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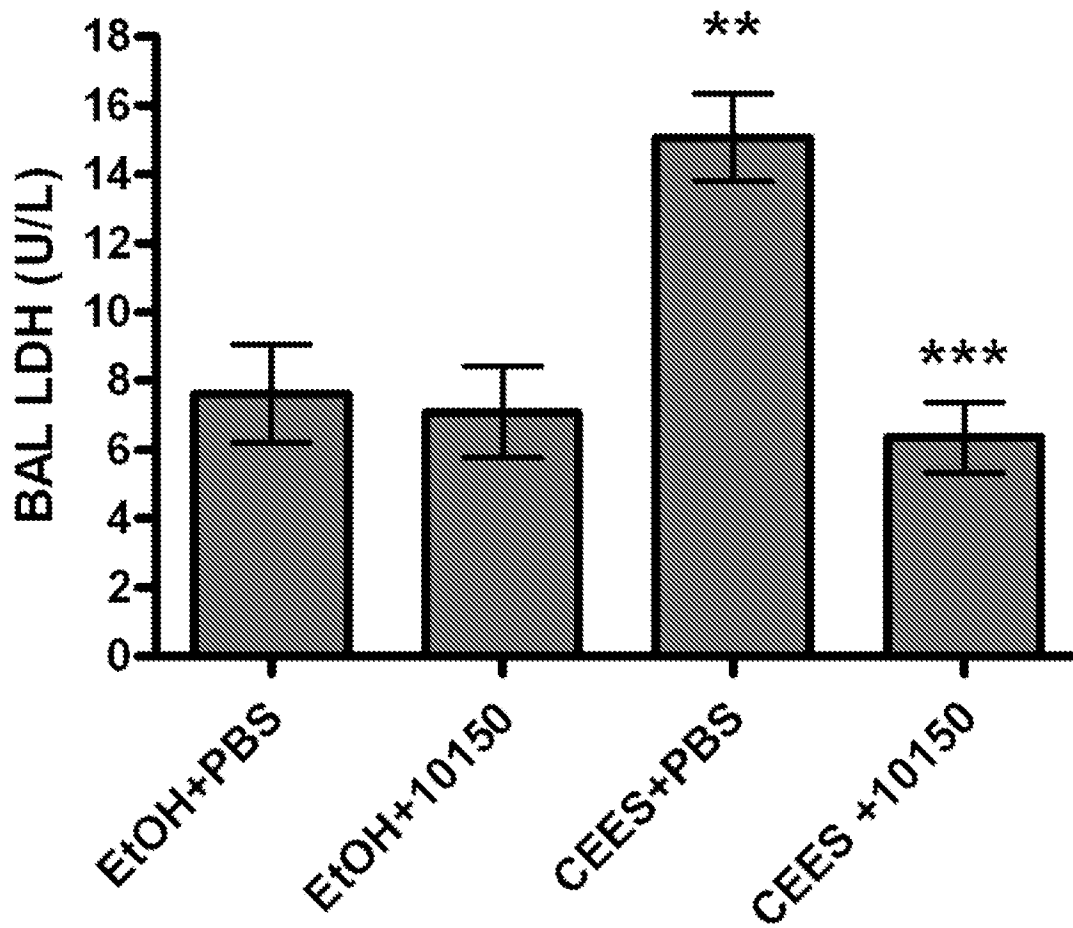


FIGURE 10

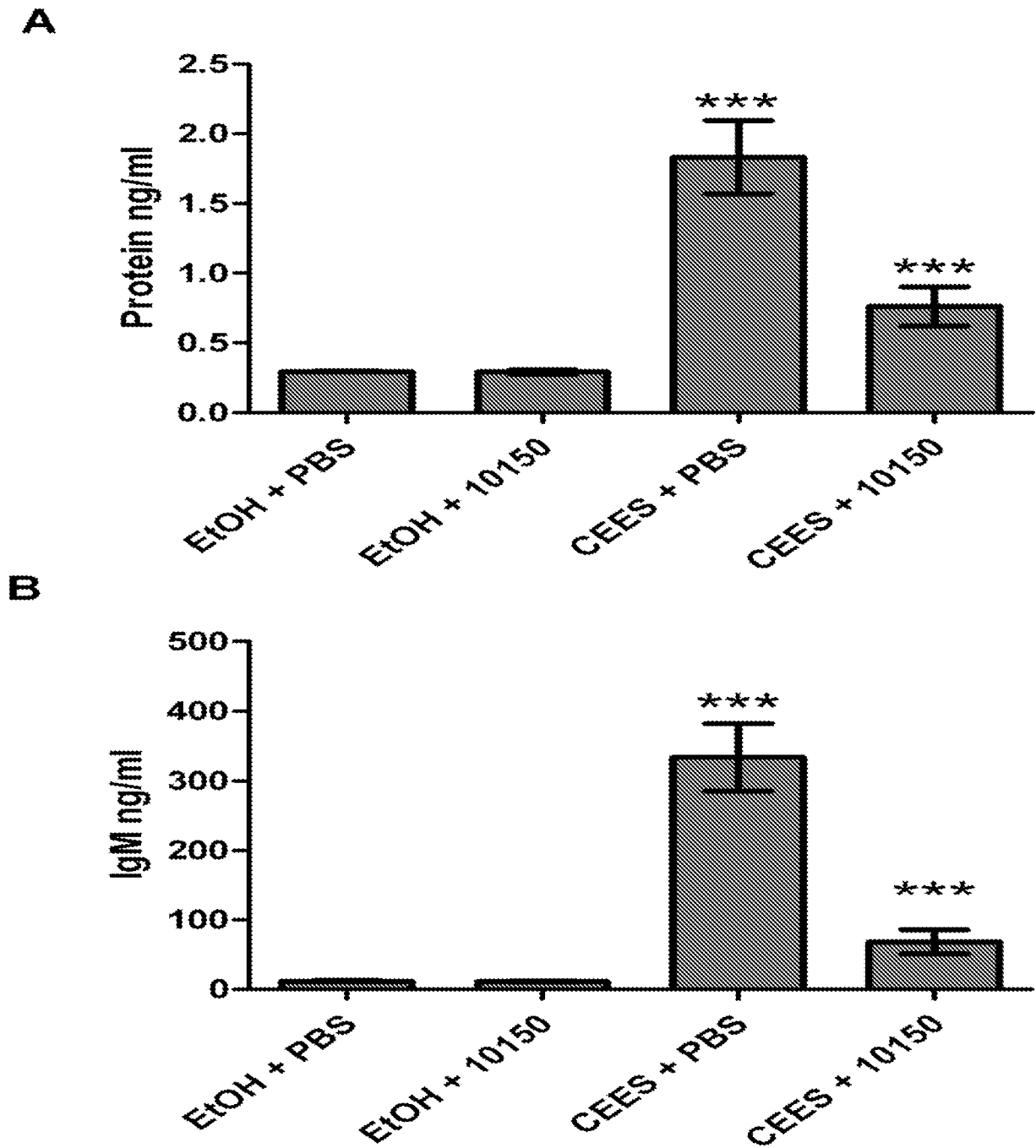


FIGURE 11

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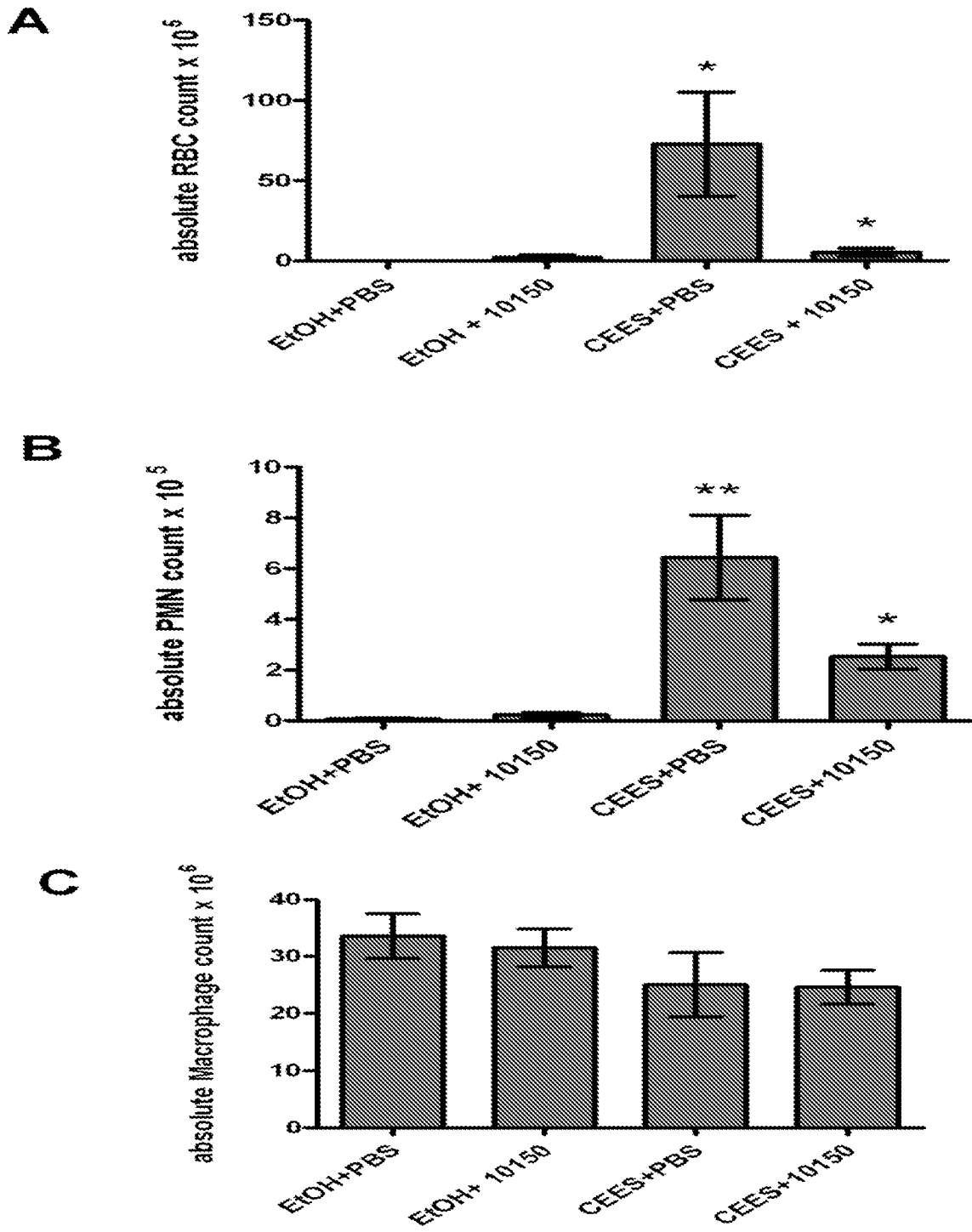


FIGURE 12

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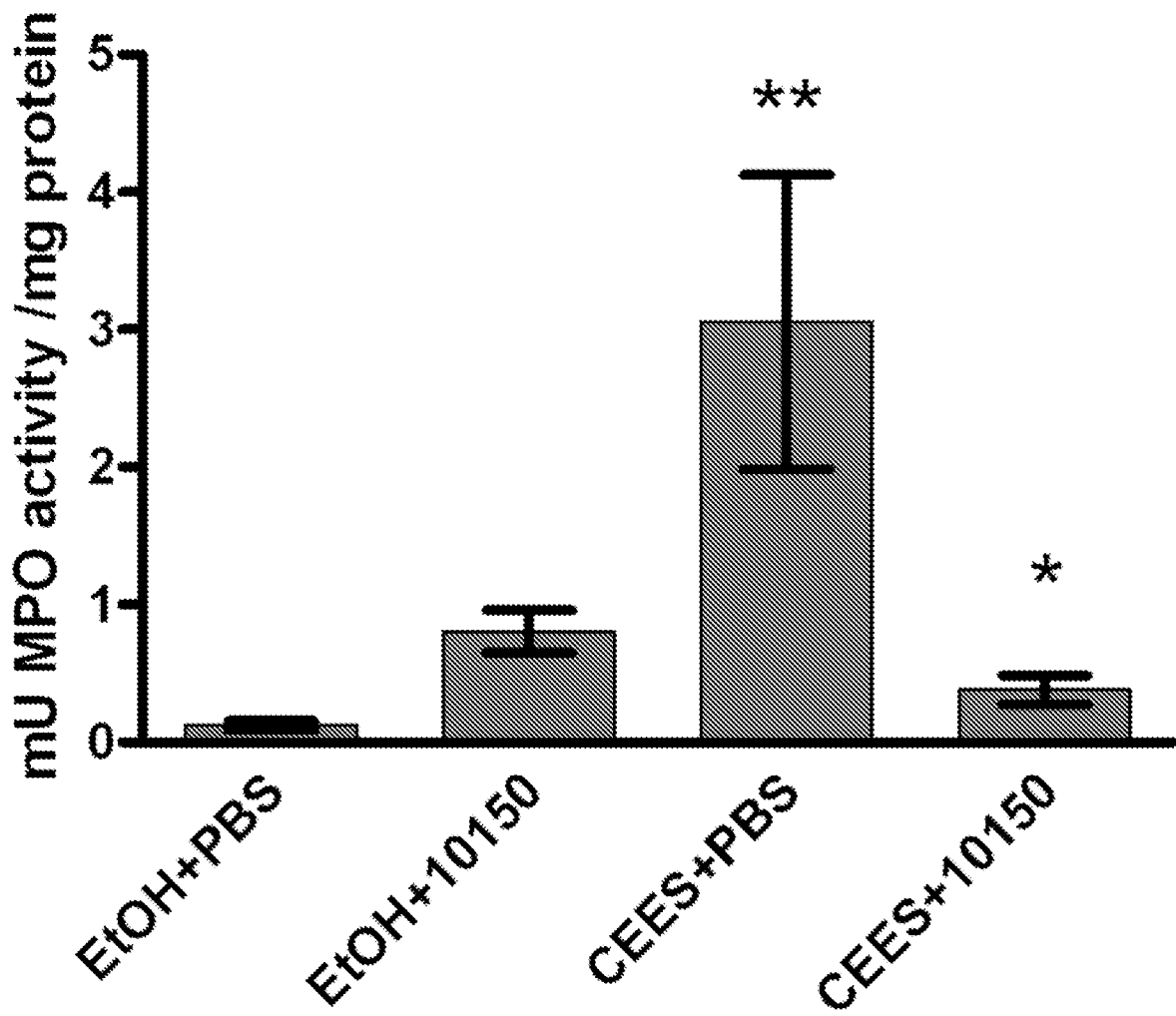


FIGURE 13

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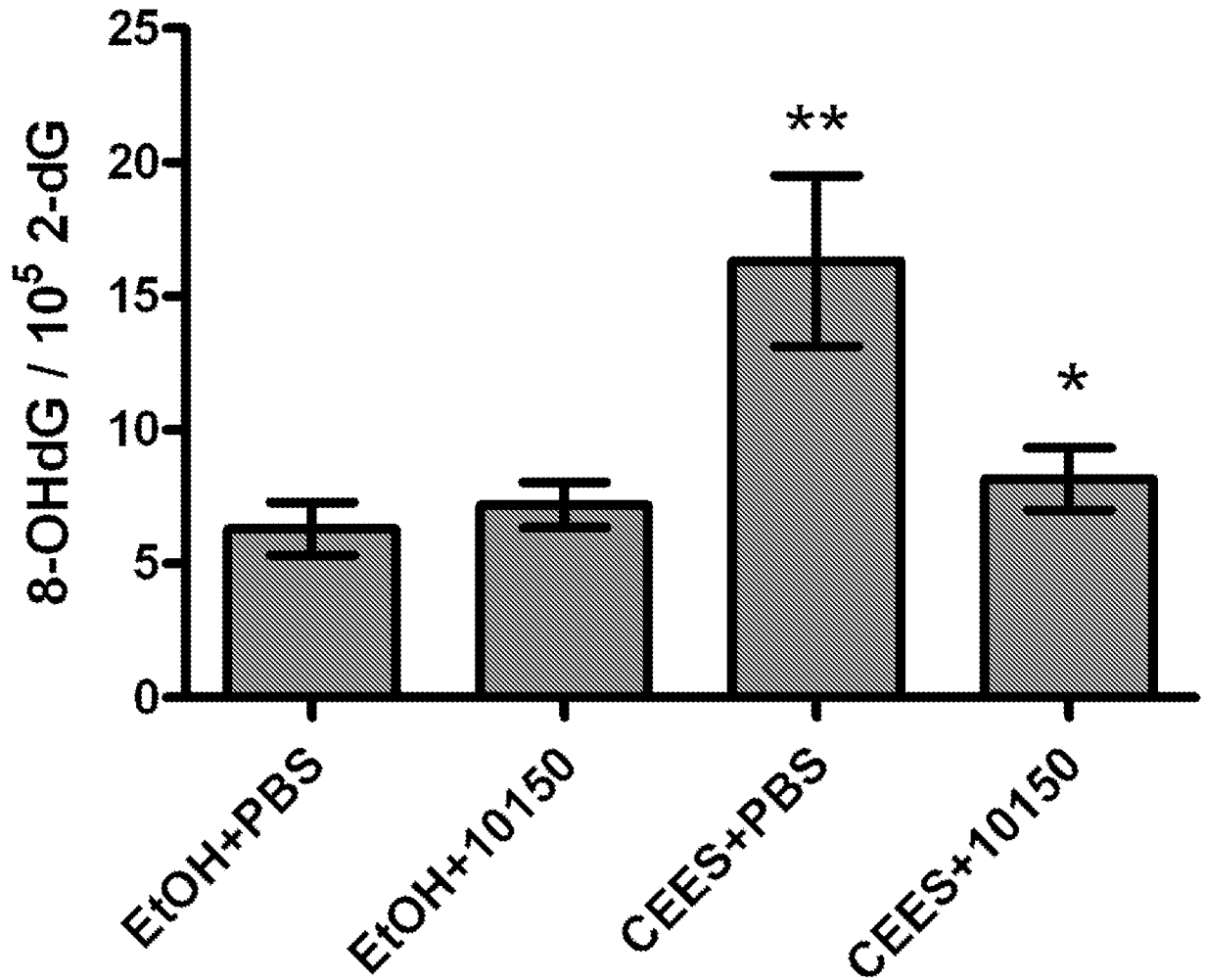


FIGURE 14

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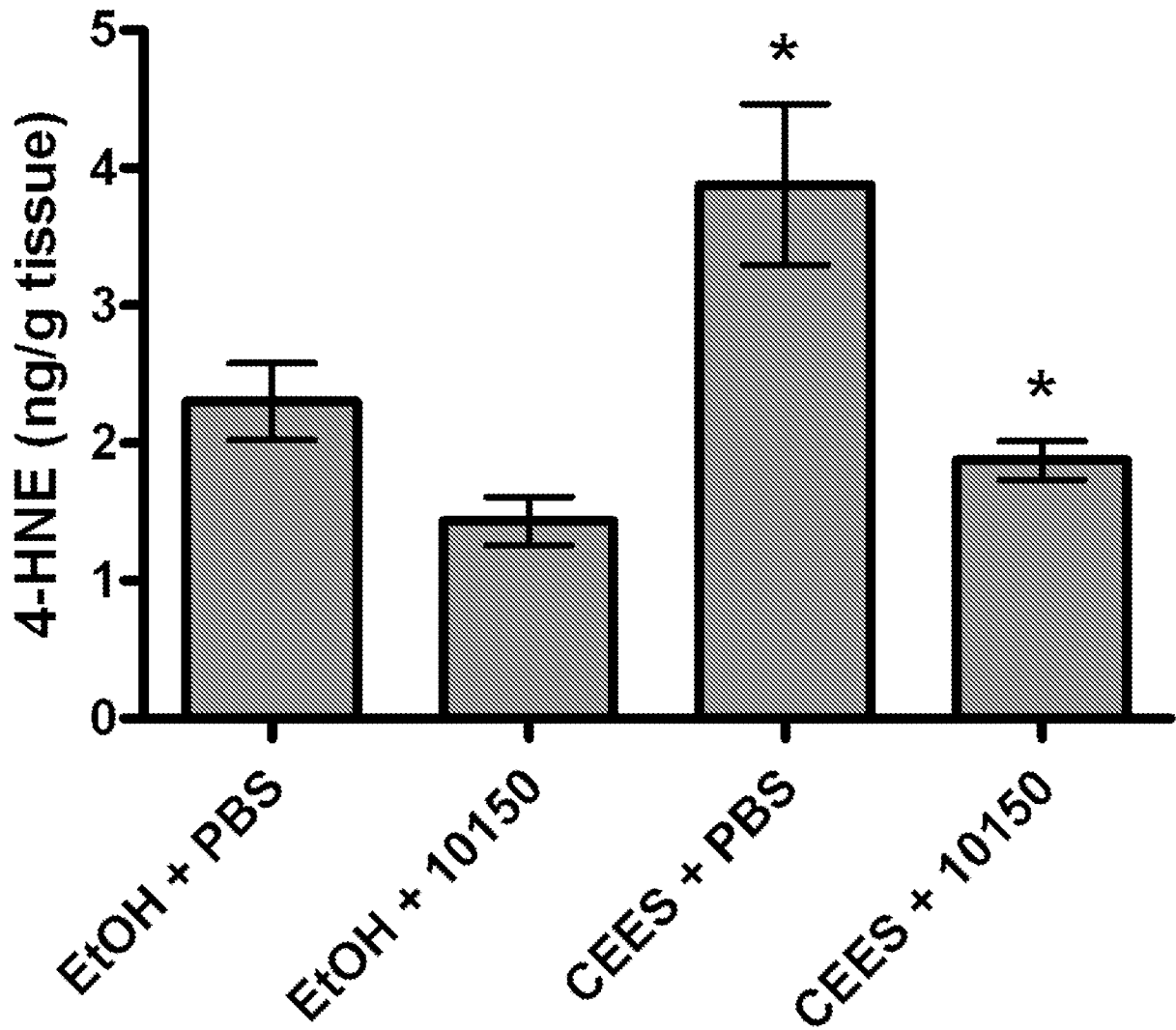


FIGURE 15