COMPOUNDS AND METHODS TO TREAT ORGANOPHOSPHORUS POISONING

Applicant: University of Iowa Research Foundation, Iowa City, IA (US)

Inventors: Daniel M. Quinn, Iowa City, IA (US); Joseph John Topczewski, Iowa City, IA (US)

Assignee: University of Iowa Research Foundation, Iowa City, IA (US)

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ABSTRACT
Organophosphate (OP) nerve agents and pesticides are potent inhibitors of acetylcholinesterase (AChE). Though oxime nucleophiles can reactivate an AChE-phosphyl adduct, the adduct can undergo a reaction called aging, leading to an aged-AChE adduct. The invention provides compounds and methods that can be used to reactivate an aged-AChE adduct. Such compounds and methods are useful to counteract organophosphorus poisoning.

10 Claims, 2 Drawing Sheets

References Cited
Ohio Supercomputer Center publication, Apr. 5, 2011.*

Primary Examiner — Janet I. Andres
Assistant Examiner — Daniel Carcanague
Attorney, Agent, or Firm — Viksins Harris & Padys PLLP
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Topczewski et al., “Resurrection of an Aged Acetylcholinesterase-Organophosphate Complex” 3rd Postdoctoral Research Symposium, University of Illinois at Urbana Champaign, Champaign, IL, Jan. 25, 2013.


Wandhammer et al., “A step toward the reactivation of aged cholinesterases—Crystal structure of ligands binding to aged human butyrylcholinesterase”, *Chemico-Biological Interactions* vol. 203 (1), 19-23 (2012).

* cited by examiner
Figure 1

\[
\begin{align*}
\text{AChE} + \text{H}_3\text{C}-\text{PO}_2\text{R} & \rightarrow \text{Inhibition} \\
\text{Free Serine Residue} & \rightarrow \text{Oxime Reactivation} \\
\text{AChE-OP Adduct} & \rightarrow \text{Aging} \\
\text{Resurrection} & \rightarrow \text{Aged Adduct}
\end{align*}
\]
Experimental: hACHe (1.25)
Treat enzyme with OP (Sarin analog) solution
Incubate at 27°C for 10 min

Experimental: hACHe (1.25)
Sepahadex G-50 Column
Dilution step
Experimental: inhibited hACHe (1.26)
Experimental: inhibited hACHe (1.870)
Incubate aliquot with 2-PAM 30 min
Experimental: recovered hACHe (1.23,400)
Experimental: recovered hACHe (1.26,000)

In Cell Final Assay: 100 uM 2-PAM
AGING CONTROL
Perform at t=0hr, t=48hrs, and at each Resurrection time point
Ellm an Assay Buffer: 50mM Phosphate Buffer, pH=7.3 Residual BSA from enzyme

Compound 100 Kppp=177uM
Buffer throughout: 0.1% (v/v) BSA 50mM Phosphate Buffer, pH=7.3

Experimental: inhibited hACHe (1.26)
Incubate at 27°C for 48 hr

Experimental: inhibited hACHe (1.433)
Incubate aliquot with 100 uM
Experimental: recovered hACHe (1.11,700)
Experimental: recovered hACHe (1.13,000)

In Cell Final Assay: 100 uM 2-PAM
AGING CONTROL
Perform at t=0hr, t=48hrs, and at each Resurrection time point
Ellm an Assay Buffer: 50mM Phosphate Buffer, pH=7.3 Residual BSA from enzyme

Control: hACHe (1.26)
Treat enzyme with Acetonitrile solvent
Incubate at 27°C for 48 hr

Control: hACHe (1.26)
Sephadex G-50 Column
Dilution Step
Control: hACHe (1.870)
Experimental: inhibited hACHe (1.26)
Incubate aliquot with 2-PAM 30 min
Control: hACHe (1.23,400)
Experimental: inhibited hACHe (1.11,700)

Control: hACHe (1.11,700)
Control: hACHe (1.13,000)
Ellm an Assay Buffer: 50mM Phosphate Buffer, pH=7.3 Residual BSA from enzyme

FIG. 2
1

COMPONDS AND METHODS TO TREAT ORGANOPHOSPHORUS POISONING

RELATED APPLICATION

This patent application claims the benefit of priority of U.S. application Ser. No. 61/756,311 filed Jan. 24, 2013. The content of this provisional application is hereby incorporated herein in its entirety.

STATEMENT OF GOVERNMENT SUPPORT

This invention was made with government support under Grant No. 5 R21 NS076430 awarded by the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

Organophosphorus (OP) agents have been used as both pesticides and chemical warfare agents for most of the past century (Mercy, G., et al., Acc. Chem. Res. 2012, 45, 756; and Jokanovic, M.; Prostran, M. Curr. Med. Chem. 2009, 16, 2177). Pesticides based on phosphate or thio phosphate agents (e.g. parathion, diazinon, or malathion) are or have been used in domestic and commercial agriculture to protect crops from a variety of destructive species. Despite numerous efforts to ban or limit the use of OP pesticides, their continued use results in over 200,000 fatalities and over 1 million instances of morbidity annually due to OP exposure. Phosphonate nerve agents, including sarin, soman, VX, and tabun, are extremely toxic and are considered a serious threat to national security due to their potential use in terrorist actions (See Millard, C. B.; et al., Biochem. 1999, 38, 7032; Sanson, B.; et al., J. Med. Chem. 2009, 52, 593; Carletti, E.; et al., J. Med. Chem. 2010, 53, 4002; and Masson, P.; Nachon, F.; Lockridge, O. Chem. Bio. Interact. 2010, 187, 157). No compounds have been reported that are able to recover AChE activity once aging has occurred, and therefore there are no known antidotes against aged AchE-OP adducts. See Mercy, G., et al., Acc. Chem. Res. 2012, 45, 756; Kalisiak, J.; et al., J. Med. Chem. 2011, 54, 3319; Kalisiak, J.; et al., J. Med. Chem. 2012, 55, 465; Mercy, G.; et al., Chem. Commun. 2011, 47, 5295; and Sit, R. et al., J. Bio. Chem. 2011, 286, 19422.

Currently there is a need for compounds and methods that can be used to reactivate the aged-AChE adduct. Such compounds and methods would be useful to counteract organophosphorus poisoning.

SUMMARY OF THE INVENTION

Applicant has discovered a class of compounds and a method that can be used to reanimate an aged-AChE adduct. Because the aged complex has long been thought of as a dead enzyme, this concept has been termed “resurrection” of the aged adduct (FIG. 1).

Accordingly, the invention provides a method for reactivating an aged-AChE adduct comprising contacting the aged-AChE adduct with an alkylating agent that leads to reactivation of the aged-AChE adduct.

The invention provides a method for treating an animal (e.g. a mammal) suffering from organophosphorus poisoning comprising administering an amount of an alkylating agent effective to reactivate aged-AChE to the animal. The method can further comprise administering an agent capable of reactivating AChE (e.g. a nucleophilic oxime) to the animal. The method can also further comprise administering an acetylcholine receptor antagonist (e.g. atropine) or an antiseizure agent (e.g. diazepam) to the animal.

The invention provides a method for increasing acetylcholinesterase activity in an animal (e.g. an animal in need of such treatment) comprising administering an amount of an alkylating agent effective to reactivate aged-AChE to the animal. The method can further comprise administering an agent capable of reactivating AChE (e.g. a nucleophilic oxime) to the animal. The method can also further comprise administering an acetylcholine receptor antagonist (e.g. atropine) and or an antiseizure agent (e.g. diazepam) to the animal.

The invention also provides a compound of formula (I):

\[
\text{HCO:}\begin{array}{c}
\text{O} \\
\text{C}\text{H}_2\text{O}\text{CH}_2\text{O}\text{R}_2
\end{array}
\]

wherein:

R is (C_1-C_3)alkyl, aryl(C_1-C_3)alkyl), or —Y—Z, wherein any (C_1-C_3)alkyl is optionally substituted with one or more
halo, and wherein any aryl is optionally substituted with one or more groups independently selected from halo, cyano, nitro, carboxy, hydroxy, (C₁₋₃)alkyl, (C₁₋₃)alkoxy, (C₁₋₃)alkoxycarbonyl, (C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio, wherein any (C₁₋₃)alkyl, (C₁₋₃)alkoxy, (C₁₋₃)alkoxycarbonyl, (C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio can optionally be substituted with one or more halo;

each R₃ is independently H, halo, cyano, carboxy, CH=NOH, (C₁₋₃)alkyl, aryl, heteroaryl, aryl(C₁₋₃)
alkyl, or heteroaryl(C₁₋₃)alkyl, wherein any (C₁₋₃)alkyl is optionally substituted with one or more halo, and wherein any aryl or heteroaryl is optionally substituted with one or more groups independently selected from halo, cyano, nitro, hydroxy, (C₁₋₃)alkyl,(C₁₋₃)alkoxy,(C₁₋₃)alkanoyl,(C₁₋₃)alkoxycarbonyl,(C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio, wherein any (C₁₋₃)alkyl, (C₁₋₃)alkoxy, (C₁₋₃)alkanoyl, (C₁₋₃)alkoxycarbonyl, (C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio can optionally be substituted with one or more halo;

each X is independently a suitable counter ion;
Y is —(CH₂)ₙ— or —(CH₃)₂—O—(CH₂)ₙ—;
n is 1, 2, 3, 4, 5, or 6; and
Z is:

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 illustrates an organophosphorus agent (OP) inhibiting acetylcholinesterase (AChE) by covalently bonding to the serine residue in the catalytic triad of the active site to form an AChE-OP Adduct. If administration of an oxime is delayed, a process called aging occurs, wherein the enzyme bound phosphate experiences a solvolytic loss of an alkyl group (Aging) to form an Aged Adduct. Reactivation (Resurrection) of the Aged-Adduct to provide the AChE-OP Adduct (e.g. using a compound or method of the invention) is also illustrated.

FIG. 2 illustrates the resurrection assay procedure (Example 3) for Compound 100 ankylation and reactivation of “aged” nAChE. The assay was carried out at pH 7.5 and 27° C. Dilution concentrations of hAChE are representative of a 100 µg/ml stock solution of hAChE in 0.1% (w/v) BSA and 50 mM Phosphate Buffer (pH 7.3). The organophosphorus (OP) inhibitor was prepared in acetonitrile.

DETAILED DESCRIPTION

The following definitions are used, unless otherwise described: halo is fluoro, chloro, bromo, or iodo. Alkyl denotes both straight and branched groups; but reference to an individual radical such as propyl embraces only the straight chain radical, a branched chain isomer such as isopropyl being specifically referred to. Aryl denotes a phenyl radical or an ortho-fused bicyclic carbocyclic radical having about nine to ten ring atoms in which at least one ring is aromatic. Heteroaryl encompasses a radical of a monocyclic aromatic ring containing five or six ring atoms consisting of carbon and one to four heteroatoms each selected from the group consisting of non-peroxide oxygen, sulfur, and N(R₄), wherein R₄ is absent or is H, O, (C₁₋₃)alkyl, phenyl or benzyl, as well as a radical of an ortho-fused bicyclic heterocycle of about eight to ten ring atoms comprising one to four heteroatoms each selected from the group consisting of non-peroxide oxygen, sulfur, and N(R₄).

The term AChE-OP includes adducts formed when an organophosphorous (OP) agent binds to a residue (e.g. a serine residue) in the catalytic triad of the active site of AChE.

The term aged-AChE adduct includes adducts formed when an AChE-OP adduct experiences a solvolytic loss of an alkyl group.

The term reactivation (or resurrection) describes the process whereby an Aged-Adduct is converted to a corresponding AChE-OP Adduct (e.g. using a compound or method of the invention).

When X is a counter ion it is understood X can be any suitable counterion. Even if it lacks significant AChE reseracting activity, a salt of formula I can be useful as an intermediate for the preparation or purification of other salts of formula I that have AChE reseracting activity. Accordingly in the compounds of formula (I), X can be any counterion. For example, in an embodiment of the invention X can be “BF₄⁻, Cl⁻, Br⁻, I⁻, NO₃⁻, PF₆⁻, NO₂⁻, carbonate, C₂F₅SO₄⁻”, (where e =2-10 and f =2×1), or arylsulfonyl, wherein aryl is optionally substituted with one or more groups independently selected from halo, cyano, nitro, carboxy, hydroxy, (C₁₋₃)alkyl, (C₁₋₃)alkoxy, (C₁₋₃)alkanoyl, (C₁₋₃)alkoxycarbonyl, (C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio, wherein any (C₁₋₃)alkyl, (C₁₋₃)alkoxy, (C₁₋₃)alkanoyl, (C₁₋₃)alkoxycarbonyl, (C₂₋₅)alkanoyloxy, and (C₁₋₃)alkylthio can optionally be substituted with one or more halo.

An aged-AChE adduct includes enzyme bound phosphonates as described herein that have experienced a solvolytic loss of an alkyl group (for example, see FIG. 1: R =isopropyl for surin, pinacolyl for soman). The aged adduct can be a phosphonate ester mononion, which is intrinsically less reactive as an electrophile that the erstwhile neutral phosphonate ester of the initial phosphonyl-AChE adduct.

Specific values listed below for radicals, substituents, and runges, are for illustration only; they do not exclude other defined values or other values within defined ranges for the radicals and substituents.

Specifically, (C₁₋₃)alkyl can be methyl, ethyl, propyl, or isopropyl; (C₁₋₃)alkoxy can be methoxy, ethoxy, propoxy, or isopropoxy; (C₁₋₃)alkanoyl can be formyl, acetyl, or propanoyl; (C₁₋₃)alkoxycarbonyl can be methoxycarbonyl, ethoxycarbonyl, propoxycarbonyl, or isopropoxycarbonyl; (C₁₋₃)alkylthio can be methylthio, ethylthio, propylthio, or isopropylthio; (C₁₋₃)alkanoyloxy can be acetoxy or propanoyloxy; aryl can be phenyl, indenyl, or naphthyl; and heteroaryl can be furyl, imidazolyl, triazolyl, triazinyl, oxazoyl, isoxazoyl, thiazoyl, isothiazoyl, pyrazolyl, pyrrolyl, pyrazinyl, tetrazolyl, pyridyl, (or its N-oxide), thienyl, pyrimidinyl (or its N-oxide), indolyl, isoquinolyl (or its N-oxide) or quinolyl (or its N-oxide).

The compounds of formula I can be formulated as pharmaceutical compositions and administered to a mammalian host, such as a human patient in a variety of forms adapted to the chosen route of administration, e.g., orally or parenterally, by intravenous, intramuscular, topical or subcutaneous routes.
Thus, the present compounds may be systemically administered, e.g., orally, in combination with a pharmaceutically acceptable vehicle such as an inert diluent or an assimilable edible carrier. They may be enclosed in hard or soft shell gelatin capsules, may be compressed into tablets, or may be incorporated directly with the food of the patient\'s diet. Oral therapeutic administration, the active compound may be combined with one or more excipients and used in the form of ingestible tablets, buccal tablets, troches, capsules, elixirs, suspensions, syrups, wafers, and the like. Such compositions and preparations should contain at least 0.1% of active compound. The percentage of the compositions and preparations may, of course, be varied and may conveniently be between about 2 to about 60% of the weight of a given unit dosage form. The amount of active compound in such therapeutically useful compositions is such that an effective dosage level will be obtained.

The tablets, troches, pills, capsules, and the like may also contain the following: binders such as gum tragacanth, aca- cin, corn starch or gelatin, excipients such as dilucidal phosphoric acid, a disintegrating agent such as corn starch, potato starch, alginic acid and the like; a lubricant such as magnes- ium stearate; and a sweetening agent such as sucrose, fructose, lactose or aspartame or a flavoring agent such as peppermint, oil of wintergreen, or cherry flavoring may be added. When the unit dosage form is a capsule, it may contain, in addition to materials of the above type, a liquid carrier, such as a vegetable oil or a polyethylene glycol. Various other materials may be present as coatings or to otherwise modify the physical form of the solid unit dosage form. For instance, tablets, pills, or capsules may be coated with gelatin, wax, shelling or sugar and the like. A syrup or elixir may contain the active compound, sucrose or fructose as a sweetening agent, methyl and propylparabens as preservatives, a dye and fla- voring such as cherry or orange flavor. Of course, any material used in preparing any unit dosage form should be pharma- ceutically acceptable and substantially non-toxic in the amounts employed. In addition, the active compound may be incorporated into sustained-release preparations and devices. The active compound may also be administered intraveneously or intraperitoneally by infusion or injection. Solutions of the active compound or its salts can be prepared in water, optionally mixed with a nontoxic surfactant. Dispersions can also be prepared in glycerol, liquid polyethylene glycol, triacetin, and mixtures thereof and in oils. Under ordinary conditions of storage and use, these preparations may contain a preservative to prevent the growth of microorganisms. The pharmaceutical dosage forms suitable for injection or infusion can include sterile aqueous solutions or dispersions or sterile powders comprising the active ingredient which are adapted for the extemporaneous preparation of sterile inject- able or insusbsible solutions or dispersions, optionally encapsu- lated in liposomes. In all cases, the ultimate dosage form should typically be sterile, fluid and stable under the condi- tions of manufacture and storage. The liquid carrier or vehicle can be a solvent or liquid dispersion medium comprising, for example, water, ethanol, a polyol (for example, glycerol, propylene glycol, liquid polyethylene glycols, and the like), vegetable oils, nontoxic, glycerol esters, and suitable mixtures thereof. The proper fluidity can be maintained, for example, by the formation of liposomes, by the maintenance of the required particle size in the case of dispersions or by the use of surfactants. The prevention of the action of microorgan- isms can be brought about by various antibacterial and anti- fungal agents, for example, parabens, chlorobutanol, phenol, sorbic acid, thimerosal, and the like. In many cases, it will be preferable to include isotonic agents, for example, sugars, buffers or sodium chloride. Prolonged absorption of the injectable compositions can be brought about by the use in the compositions of agents delaying absorption, for example, aluminum monostearate and gelatin.

Sterile injectable solutions can be prepared by incorporat- ing the active compound in the required amount in the appro- priate solvent with various other ingredients enumerated above, as required, followed by filter sterilization. In the case of sterile powders for the preparation of sterile injectable solutions, suitable methods of preparation include vacuum drying and the freeze drying techniques, which yield a pow- der of the active ingredient plus any additional desired ingre- dient present in the previously sterile-filtered solutions.

For topical administration, the present compounds may be applied in pure form, e.g., when they are liquids. However, it will generally be desirable to administer them to the skin as compositions or formulations, in combination with a derma- tologically acceptable carrier, which may be a solid or a liquid.

Useful solid carriers include finely divided solids such as talc, clay, microcrystalline cellulose, silica, alumina and the like. Useful liquid carriers include water, alcohol or glycols or water-alcohol/glycol blends, in which the active com- pounds can be dissolved or dispersed at effective levels, optionally with the aid of non-toxic surfactants. Adjuvants such as fragrances and additional antimicrobial agents can be added to optimize the properties for a given use. The resultant liquid compositions can be applied from absorbent pads, used to impregnate bandages and other dressings, or sprayed onto the affected area using pump-type or aerosol sprayers.

Thickeners such as synthetic polymers, fatty acids, fatty acid salts and esters, fatty alcohols, modified celluloses or modified mineral materials can also be employed with liquid carriers to form spreadable pastes, gels, ointments, soaps, and the like, for application directly to the skin of the user. Examples of useful dermatological compositions which can be used to deliver the compounds of formula I to the skin are known to the art; for example, see Jacquet et al. (U.S. Pat. No. 4,608,392), Geria (U.S. Pat. No. 4,992,478), Smith et al. (U.S. Pat. No. 4,559,157) and Wurtzman (U.S. Pat. No. 4,820,508).

Useful dosages of the compounds of formula I can be determined by comparing their in vitro activity, and in vivo activity in animal models. Methods for the extrapolation of effective dosages in mice, and other animals, to humans are known to the art; for example, see U.S. Pat. No. 4,938,949.

The amount of the compound, or an active salt or derivative thereof, required for use in treatment will vary not only with the particular salt selected but also with the route of admin- istration, the nature of the condition being treated and the age and condition of the patient and will be ultimately at the discretion of the attendant physician or clinician. The desired dose may conveniently be presented in a single dose or as divided doses administered at appropriate intervals, for example, as two, three, four or more sub-doses per day. The sub-dose itself may be further divided, e.g., into a number of discrete loosely spaced administrations; such as multiple inhalations from an insufflator or by application of a plurality of drops into the eye.

Compounds of the invention can also be administered in combination with other therapeutic agents, for example, other agents that are useful for the treatment of organophosphorus poisoning.

When the compounds of the invention are administered to counteract organophosphorus poisoning, for example in a chemical warfare situation, they may be self-administered, for example, by means of a syringe or a spring-loaded syringe. When the compounds of the invention are adminis- tered as a combination with other agents (e.g. 2-PAM, atro- pine, and/or diazepam), the combination may also be adminis- tered by a single injection device such as, for example, a
syringe or a spring-loaded syringe capable of simultaneously administering the one or more of the agents.

Synthesis

The synthesis of the N-methyl-methoxy-pyridinium compounds can be conducted by exposure of starting pyridines to trialkoxonium (e.g., trimethoxonium) tetrafluoroborate or another alkylating agent (e.g., MeOTf) in a suitable solvent (e.g., methylene chloride or toluene) before or after oxime formation as illustrated in Scheme 1.

The invention will now be illustrated by the following non-limiting Examples.

**EXAMPLES**

**Example 1**

**Synthesis of the Compound (100)**

A 3 mL glass vial was equipped with a rubber septum and magnetic stir bar. The vial was brought into a glove box and charged with trimethoxonium tetrafluoroborate (198 mg, 1.33 mmol). The vial was sealed and removed from the glove box. A separate 3 mL vial was charged with 2-methoxy-6-pyridinecarboxaldehyde (Aldrich #662933, 184 mg, 1.34 mmol) and was dissolved in CH₂Cl₂ (1.5 mL). The solution of pyridine was added via syringe onto the solid trimethoxonium tetrafluoroborate at room temperature. The vial which contained the pyridine was rinsed with CH₂Cl₂ (1 mL) and the rinse solution was injected into the reaction vial. The reaction vial was kept at room temperature and stirring was maintained at ca. 400-600 rpm. Over the course of the reaction (17 h), the solid trimethoxonium tetrafluoroborate gradually dissolved, the solution clarified, and an oil gradually formed. At the end of the reaction, hexanes (2 mL) were added after which stirring was stopped. Any solid or oil was allowed to settle and the solvent was removed by glass pipette. The solid or oil was then rinsed with several portions of hexanes followed by diethyl ether. Residual solvent was then removed in vacuo to provide the compound N-methyl-6-methoxy-2-pyridinecarboxaldehyde tetrafluoroborate. This oil was used for oxime formation without further purification.

A flask was charged with NaOCH₃ (18.5 mg, 0.34 mmol) and hydroxylamine hydrochloride (31 mg, 0.44 mmol) and the solids were taken up in MeOH (2 mL) and left at room temperature for 5 min. The preceding aldehyde (80 mg, 0.34 mmol) was dissolved in MeOH (3 mL) and was injected into the solution of hydroxylamine. After 18 hr at room temperature, the reaction was diluted with ethyl ether, filtered through sand, and concentrated in vacuo. The residue was taken up in acetonitrile and filtered through celite and concentrated in vacuo. The residue was taken up in acetone and slow diffusion of hexanes into the solution provided compound 100 (37 mg, 43%) as a crystalline salt.

**Example 2**

**Synthesis of the Compound (101)**

...
A 3 mL glass vial was equipped with a rubber septum and magnetic stir bar. The vial was brought into a glove box and charged with MeOTf (116 µL, 1.06 mmol) by micropipette. The vial was sealed and removed from the glove box. A separate 3 mL vial was charged with 4-methoxy-2-pyridin-2-ylcarboxaldehyde (Astatech C10253, 145 mg, 106 mmol) and was dissolved in PhMe (1 mL). The solution of pyridine was added via syringe onto the MeOTf at room temperature. The vial which contained the pyridine was rinsed with PhMe (0.5 mL) and the rinse solution was injected into the reaction vial. The reaction vial was kept at room temperature and stirring was maintained at ca. 400-600 rpm. After 20 h, hexanes (2 mL) were added after which stirring was stopped. Any solid or oil was allowed to settle and the solvent was removed by glass pipette. The solid or oil was then rinsed with several portions of hexanes followed by diethyl ether. Residual solvent was then removed in vacuo to provide the compound N-methyl-4-methoxy-2-pyridin-2-ylcarboxaldehyde trflate (300 mg, 94%). This oil was used for oxime formation without further purification.

A flask was charged with NaOCH₂ (18 mg, 0.34 mmol) and hydroxylamine hydrochloride (27 mg, 0.39 mmol) and the solids were taken up in MeOH (1 mL) and left at room temperature for 5 min. The preceding aldehyde (79 mg, 0.26 mmol) was dissolved in MeOH (2 mL) and was injected into the solution of hydroxylamine. After 18 hr at room temperature, the reaction was diluted with ethyl ether, filtered through sand, and concentrated in vacuo. The residue was purified by C-18 reverse phase chromatography (water/acetonitrile, 0-100%) and concentrated under a stream of air, which afforded compound 101 (18 mg, 22%) as a crystalline salt.

**Example 3**

Resurrection of Aged-AChE by Compound 100

Recombinant human acetylcholinesterase (hAChE) was irreversibly inhibited by exposure to an organophosphate (OP) analog of Sarin, 7-(isopropyl methylphosphonyl)-4-methylumbelliferyl (Timperley, C., et al., J. Fluor. Chem., 2006, 127, 1554-1563). The fully inhibited hAChE-OP adduct was separated on a Sephadex G-50 Quick Spin column to remove excess nerve agent, and it was “aged” for 48 hours at 27°C. Uninhibited hAChE was prepared following the

“aged” hAChE (% AChE\textsubscript{aged}, or residual hAChE, activity as defined by Equation (1). This % AChE\textsubscript{aged} is the ratio of the initial rates for OP inhibited hAChE (AChE\textsubscript{inhibited}) and uninhibited hAChE (AChE\textsubscript{free}) catalyzed hydrolysis of ATCh.

\[
% \text{AChE}_{\text{aged}} = \frac{\text{rate of AChE}_{\text{inhibited}}}{\text{rate of AChE}_{\text{free}}} \times 100
\]  

FIG. 2 depicts the procedural steps for a resurrection assay that can be used to determine the activity of a test compound (e.g. Compound 100). Resurrection assays were performed by preparing a 100 µL incubation solution of 0.024 µg of “aged” hAChE in 0.1% (w/v) BSA, 50 mM phosphate buffer (pH 7.3), and 885 µM Compound 100. “Aged” hAChE was incubated for 1 hour, 4 hour, and 24 hour periods at 27°C. Following each incubation period, a 10 µL aliquot of the “aged” hAChE incubation solution was assayed in 50 mM phosphate buffer (pH 7.3), 0.3 mM ATCh and 0.45 mM DTNB following a 30 minute incubation with 100µM 2-PAM and a total volume of 300 µL. The percent of “aged” hAChE reactivated (AChE\textsubscript{react}) by 2-PAM was calculated using Equation (2), which is the ratio of the initial rates of “aged” hAChE (AChE\textsubscript{aged}) and AChE\textsubscript{free} catalyzed hydrolysis of ATCh assayed following each incubation with Compound 100. From Equation (3), the percent of resurrected hAChE was determined.

\[
% \text{AChE}_{\text{react}} = \frac{\text{rate of AChE}_{\text{aged}}}{\text{rate of AChE}_{\text{free}}} \times 100
\]

\[
% \text{AChE}_{\text{res}} = \% \text{AChE}_{\text{react}} - \% \text{AChE}_{\text{aged}}
\]

Resurrection assay data is shown in the following table for 1.77 mM Compound 100, where ν, is the initial rates for AChE\textsubscript{aged} and AChE\textsubscript{free}, catalyzed hydrolysis of ATCh. Background rates were measured in the absence of hAChE. All experiments were done in duplicate.

<table>
<thead>
<tr>
<th>Time, hours</th>
<th>ν/ (AChE\textsubscript{aged}, m/min)</th>
<th>ν/ (AChE\textsubscript{free}, m/min)</th>
<th>Background Rate, m/min</th>
<th>% AChE\textsubscript{react}</th>
<th>% AChE\textsubscript{aged}</th>
<th>% AChE\textsubscript{res}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>11.05 (±1.3)</td>
<td>197.50 (±8.9)</td>
<td>6.37 (±0.2)</td>
<td>2.45 (±0.7)</td>
<td>1.16 (±0.06)</td>
<td>1.28 (±0.8)</td>
</tr>
<tr>
<td>4.00</td>
<td>16.66 (±1.0)</td>
<td>184.70 (±0.7)</td>
<td>6.56 (±0.1)</td>
<td>5.67 (±0.6)</td>
<td>1.16 (±0.06)</td>
<td>4.50 (±0.6)</td>
</tr>
<tr>
<td>12.00</td>
<td>20.56 (±0.1)</td>
<td>191.60 (±0.8)</td>
<td>8.75 (±1)</td>
<td>6.46 (±1.1)</td>
<td>1.16 (±0.06)</td>
<td>5.30 (±1.1)</td>
</tr>
<tr>
<td>24.00</td>
<td>21.90 (±1.5)</td>
<td>160.70 (±14)</td>
<td>8.68 (±0.1)</td>
<td>8.70 (±1.3)</td>
<td>0.00 (±0.06)</td>
<td>8.70 (±1.3)</td>
</tr>
<tr>
<td>48.00</td>
<td>21.75 (±1.3)</td>
<td>213.60 (±13)</td>
<td>7.25 (±0.3)</td>
<td>7.03 (±0.8)</td>
<td>0.00 (±0.06)</td>
<td>7.03 (±0.8)</td>
</tr>
</tbody>
</table>

All publications (including Topczewski et al., Organic Letters, 15, 1084-1087 (2013), patents, and patent documents are incorporated by reference herein, as though individually incorporated by reference. The invention has been described with reference to various specific and preferred embodiments and techniques. However, it should be understood that many variations and modifications may be made while remaining within the spirit and scope of the invention.
The invention claimed is:

1. A method for reactivating an aged-AChE adduct comprising contacting the aged-AChE adduct with an alkylating agent that reactivates the aged-AChE adduct to provide an AChE-OP adduct, wherein the alkylating agent is a compound of formula (I):

wherein:
- $R_1$ is $C_1\text{-}C_3$ alkyl that is optionally substituted with one or more halo;
- each $R_2$ is independently $H$, halo, cyano, or ($C_1\text{-}C_3$) alkyl that is optionally substituted with one or more halo; and
- $X$ is $\text{BF}_3$, $\text{CF}_3\text{SO}_3^-$, $\text{F}^-$, $\text{Cl}^-$, $\text{Br}^-$, $\Gamma$, monobasic sulfate, dibasic sulfate, monobasic phosphate, dibasic phosphate, or tribasic phosphate, $\text{NO}_3^-$, $\text{PF}_6^-$, $\text{NO}_2^-$, $\text{C}_5\text{F}_3\text{SO}_3^-$ (where $e=2\text{-}10$ and $f=2\text{e}+1$), or arylsulfonyl, wherein ary1 is optionally substituted with one or more groups independently selected from halo, cyano, nitro, carboxy, hydroxy, ($C_1\text{-}C_3$)alkyl, ($C_1\text{-}C_3$)alkoxy, ($C_1\text{-}C_3$) alkanoyl, ($C_1\text{-}C_3$)alkoxyacrylonyl, ($C_1\text{-}C_3$)alkanoyloxy, and ($C_1\text{-}C_3$)alkylthio, wherein any ($C_1\text{-}C_3$)alkyl, ($C_1\text{-}C_3$)alkoxy, ($C_1\text{-}C_3$)alkanoyl, ($C_1\text{-}C_3$)alkoxyacrylonyl, ($C_1\text{-}C_3$)alkanoyloxy, and ($C_1\text{-}C_3$)alkylthio can optionally be substituted with one or more halo.

2. A method for reactivating an aged-AChE adduct in an animal having organophosphorus poisoning comprising administering to the animal an amount of an alkylating agent effective to reactivate aged-AChE to provide an AChE-OP adduct, wherein the alkylating agent is a compound of formula (I):

wherein:
- $R_1$ is $C_1\text{-}C_3$ alkyl that is optionally substituted with one or more halo;
- each $R_2$ is independently $H$, halo, cyano, or ($C_1\text{-}C_3$)alkyl that is optionally substituted with one or more halo; and
- $X$ is $\text{BF}_3$, $\text{CF}_3\text{SO}_3^-$, $\text{F}^-$, $\text{Cl}^-$, $\text{Br}^-$, $\Gamma$, monobasic sulfate, dibasic sulfate, monobasic phosphate, dibasic phosphate, or tribasic phosphate, $\text{NO}_3^-$, $\text{PF}_6^-$, $\text{NO}_2^-$, $\text{C}_5\text{F}_3\text{SO}_3^-$ (where $e=2\text{-}10$ and $f=2\text{e}+1$), or arylsulfonyl, wherein ary1 is optionally substituted with one or more groups independently selected from halo, cyano, nitro, carboxy, hydroxy, ($C_1\text{-}C_3$)alkyl, ($C_1\text{-}C_3$)alkoxy, ($C_1\text{-}C_3$) alkanoyl, ($C_1\text{-}C_3$)alkoxyacrylonyl, ($C_1\text{-}C_3$)alkanoyloxy, and ($C_1\text{-}C_3$)alkylthio, wherein any ($C_1\text{-}C_3$)alkyl, ($C_1\text{-}C_3$)alkoxy, ($C_1\text{-}C_3$)alkanoyl, ($C_1\text{-}C_3$)alkoxyacrylonyl, ($C_1\text{-}C_3$)alkanoyloxy, and ($C_1\text{-}C_3$)alkylthio can optionally be substituted with one or more halo.

3. A method for increasing acetylcholinesterase activity in an animal comprising administering to the animal an amount of an alkylating agent effective to reactivate aged-AChE to provide an AChE-OP adduct and administering to the animal an agent capable of reactivating the AChE-OP adduct and increasing acetylcholinesterase activity in the animal, wherein the alkylating agent is a compound of formula (I):