Immunodetection of Serum Albumin Adducts as Biomarkers for Organophosphorus Exposure*

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Abbreviations

OP, organophosphate; AChE, acetylcholinesterase; BChE, butyrylcholinesterase; GB, sarin; GD, soman; GF, cyclosarin; GA, tabun; HSA, human serum albumin; VX, (S-[2-(diisopropylamino)ethyl]-O-ethyl methylphosphonothioate); mAb-HSA-GD, monoclonal antibody that recognizes HSA tyrosine 411 adduct of soman; mAb-HSA-VX, monoclonal antibody that recognizes HSA tyrosine 411 adduct of VX; GSA, guinea pig serum albumin; MSA, monkey serum albumin; RSA, rat serum albumin; AcA, amino caproic acid; KLH, keyhole limpet cyanin; HSA-soman protein adduct, human serum albumin that has conjugated soman; OVAL, ovalbumin, HSA-GD, decapeptide hapten that has a soman phosphorylated tyrosine; HSA-VX, decapeptide hapten that has a VX phosphorylated tyrosine; HSA-GB, decapeptide hapten that has a GB phosphorylated tyrosine; HSA-GF, decapeptide hapten that has a GF phosphorylated tyrosine.
Abstract

A major challenge in organophosphate (OP) research has been the identification and utilization of reliable biomarkers for the rapid, sensitive and efficient detection of OP exposure. Although tyrosine (Tyr) 411 OP adducts to human serum albumin (HSA) have been suggested to be one of the most robust biomarkers in the detection of OP exposure, the analysis of HSA-OP adduct detection has been limited to techniques using mass spectrometry. Herein, we describe the procurement of two monoclonal antibodies (mAb-HSA-GD and mAb-HSA-VX) that recognized the HSA Tyr 411 adduct of soman (GD) or VX, respectively, but did not recognize non-phosphonylated HSA. We showed that mAb-HSA-GD was able to detect the HSA Tyr 411 OP adduct at a low level (i.e., human blood plasma treated with 180 nM soman) that could not be detected by mass spectrometry. mAb-HSA-GD and mAb-HSA-VX showed an extremely low level detection of GD-adducted to HSA (on the order of picograms or $10^{-12}$ g). mAb-HSA-GD could also detect serum albumin OP adducts in blood plasma samples from different animals administered GD including rat, guinea pig and monkey. The ability of the two antibodies to selectively recognize nerve agents adducted to serum albumin suggests that these antibodies could be used to identify biomarkers of OP exposure and provide a new biological approach to detect OP exposure in animals.
Introduction

Organophosphates (OPs) constitute a diverse class of chemicals that include insecticides, protease inhibitors and chemical warfare agents. The use of OP toxicants as a chemical warfare weapon is a threat to United States military personnel as well as civilians. In addition, agricultural workers who handle OP pesticides are at risk of exposure because there are more than 100 different OP pesticides used worldwide and it is estimated that globally, there are 750,000 to 3,000,000 human intoxications by OPs annually (Kwong, 2002). The worldwide level of OP exposure and the possible toxic consequences underscores the need to develop an efficient, portable, and inexpensive way to detect OPs (Chen and Mulchandani, 1998; Sogorb and Vilanova, 2002).

The acute toxic effects of OPs arise from the inhibition of acetylcholinesterase (AChE) to form a relatively stable OP-AChE adduct. AChE inhibition results in accumulation of excess acetylcholine that leads to stimulation of acetylcholine receptors that can produce convulsions and other CNS toxicity (Marrs et al., 2007). In addition to AChE inhibition, OPs also covalently modify other proteins (Schopfer et al., 2005; Wieseler et al., 2006; Thompson et al., 2010) including butyrylcholinesterase (BChE) and serum albumin.

Analysis of biomedical samples (e.g., urine and blood), can provide not only qualitative but also quantitative information about OP exposure (Marrs et al., 2007). Numerous approaches have been used in the detection of OP exposure (Worek et al., 2005; Thompson et al., 2010) including determination of inhibition of serum AChE and BChE functional activities with biochemical assays, detection of unbound OP in plasma or their decomposition products with either GC-MS
or LC-MS-MS. Other approaches include GC-MS detection of fluoride-induced reactivated AChE or BChE, and detection of AChE, BChE or albumin OP adducts with CE-MS or LC-MS-MS after proteolytic digestion of those proteins. Among these approaches, determination of inhibition of AChE and BChE functional activity in the blood is still the mainstay for quick initial screening, although determination of relative cholinesterase activity lacks sensitivity and specificity. Mass spectrometry approaches require sophisticated equipment and well-trained operators (Worek et al., 2005).

Detection of protein-OP adducts (i.e., AChE, BChE or serum albumin) as biomarkers for OP exposure has provided insight into the structural biology of OP action (Read et al., 2010; Thompson et al., 2010). Generally, the approach to detect protein-OP adducts has relied on mass spectrometry (Thompson et al., 2010) although one report showed that antibodies could be raised against phosphorylated-AChE (George et al., 2003). However, in that report, the antibodies reported to recognize the inhibited form of AChE did not distinguish OP-AChE adducts arising from different OPs (George et al., 2003). An attempt to develop antibodies against phosphorylated BChE showed that the chemical instability of phosphorylated decapeptide haptens designed to mimic phosphorylated-BChE precluded using this approach ((MacDonald et al., 2010) and unpublished observations). In addition, despite the fact that AChE and BChE are prominent targets of OP exposure, these enzymes are present at low concentrations (e.g., BChE is present at 4 µg/mL in plasma) and the OP-BChE adduct is labile (Li et al., 2007). In contrast, serum albumin is the most abundant protein in blood plasma (40,000 µg/mL, and after OP exposure, OPs form a stable adduct (e.g., with HSA at Tyr 411) on the basis of LC-MS analysis of proteolytic digests (Li et al., 2008). Thus, albumin is a functional scavenger of OPs, resulting
in a stable OP adduct after exposure. It has been estimated that 1-2% of HSA forms a stable OP adduct after OP exposure (Ding et al., 2008). Based on the instability of phosphonylated adducts to AChE and BChE, the detection of HSA-OP adducts represent a more feasible strategy to detect *in vivo* biomarkers of OP exposure because the abundance of serum albumin is ten thousand times more than either AChE or BChE (Ding et al., 2008) and the Tyr 411 adduct is extremely stable (8). Tyr 411 OP adducts of HSA has been reported in a number of cases of OP exposure (Peeples et al., 2005; Li et al., 2010; Lockridge and Schopfer, 2010; Marsillach et al., 2011).

Protein sequence alignment of serum albumin indicates that across different species including human, rat, and guinea pig, the region surrounding Tyr 411 is highly conserved (Figure 1). We therefore chose this region (i.e., amino acids 408-417, LVRYTKKVPQ, in HSA) as the epitope to synthesize phosphonylated antigens and haptens. Based on the three-dimensional structure of HSA, Tyr 411 lies on the surface of the protein (Ding et al., 2008) and Tyr 411 is apparently readily accessible and efficiently being attacked by OPs to form stable covalent adducts of HSA. This may explain why Tyr 411 of HSA is preferentially phosphonylated if treated with OPs (Li et al., 2008).

In the present report, we discuss the rationale and the successful generation of five monoclonal antibodies (in which two were studied in detail) that were raised against four different phosphonylated decapeptides corresponding to the region surrounding Tyr 411 in HSA. Two of the monoclonal antibodies selectively recognized GD or VX adducts, respectively, at Tyr 411 on HSA. The two antibodies were shown to possess great sensitivity (i.e., as little as $10^{-12}$ g of antigen detected in blood plasma samples) and detected OP-adducted serum albumin from
various biological samples prepared from \textit{in vitro} and \textit{in vivo} OP exposure experiments. The antibodies also stereoselectively recognized OP-adducted to HSA. Because the OPs used in these studies possess two centers of chirality, four possible OP adducts could form. In the case of GD adducted to HSA, one of the adducts was selectively recognized over the other one. Two monoclonal antibodies (i.e., mAb-HSA-GD and mAb-HSA-VX) were successfully used in studies to detect OP adducts of serum albumin in different species including human, rat, guinea pig, and monkey. The availability of the two monoclonal antibodies not only provides a powerful tool in basic research, but also could be used to identify biomarkers of OP exposure and provide a new approach to detect OP exposure in animals.

\textbf{Materials and Methods}

\textbf{Biological and chemical reagents}

Buffers, reagents and solvents were purchased from VWR Scientific, Inc. (San Diego, CA) in the highest purity commercially available. The nerve agent model compounds and their corresponding \textit{Sp}, \textit{Rp} isomers were synthesized as previously described (Berman and Leonard, 1989; Barakat et al., 2009). The nerve agent model compounds are toxic and should be handled with extreme care. Chemical waste containing nerve agent model compounds were hydrolyzed by overnight incubation with 2.5 M NaOH and 10\% ethanol before disposal. Goat anti-mouse antibodies conjugated with horseradish peroxidase (HRP) and SuperSignal West Pico Chemiluminescent substrate was purchased from Pierce (Rockford, IL). Molecular biology reagents were purchased from Life Technologies (Carlsbad, CA) unless otherwise specified.

\textbf{Synthesis of para-nitrophenyl esters of nerve agent model compounds}
The synthesis of para-nitrophenyl esters of nerve agent model compounds was accomplished by combining the corresponding nerve agent monochloridates (50 mg, 0.25 mmol) (11) with triethylamine (150 mg, 0.9 mmol), dimethylaminopyridine (5 mg, 0.04 mmol) at 4 ºC in CH₂CCl₂. After addition of para-nitrophenol (150 mg, 1.1 mmol) and stirring at room temperature for 5 hours, the mixture was cooled to 4 ºC, and made basic, and the separated organic fraction was evaporated to dryness and chromatographed to afford the desired products in 78-91% yield. Each product was fully characterized by NMR.

Phosphonylation of HSA in the presence of para-nitrophenyl esters of GB, GD and VX

The incubation was comprised of 200 nM of the para-nitrophenyl esters of GB, GD and VX (made up in a stock solution of CH₃CN) and 10 nM of HSA in Tris-HCl buffer (10 mM, pH 8.0) in a total incubation volume of 0.6 ml. The incubation was initiated after thorough mixing and continuously monitored at 400 nm with a Cary UV-vis spectrophotometer (Santa Clara, CA). The progress curves were plotted as a function of absorbance increase versus time. The half life and rate constants were determined (n=3).

Characterization of phosphonylated peptide-amino caproic acid hapten purity and aqueous stability

The purity of phosphonylated peptides was determined by HPLC. Phosphonylated peptides were run on a Beckman Gold HPLC column using 0.1% TFA in water/acetonitrile and a reverse phase C18 column using a Hitachi 2000 HPLC (Hitachi Inc., Dallas, TX). HPLC data was reported for final, purified peptides. Final purities ranged from 92-99%. Peptide purity for each peptide is shown in Table 1. The stability of the phosphonylated peptides was determined by
mass spectrometry (MS). Each phosphonylated peptide was prepared to final concentration of 1 mg/mL and an internal standard (IS) was included to assist MS quantification (pH 7.0, 25 °C). At the appropriate time point, an aliquot of each sample was injected into the MS (Hitachi M-8000, Hitachi Inc.) using ESI ionization in the positive mode. Signal intensities for each phosphorylated peptide were tabulated and compared to the signal intensities of the internal standard peptide for each run (Peptide/IS). Peptide/IS for each day was normalized to the value obtained at Day 0 and this value was multiplied by 100 to get % remaining phosphorylated peptide. Plots of % Remaining vs. Time (Days) were made in Excel. Half lives were calculated for each phosphorylated peptide shown in Table 1.

Preparation of antigens and conjugation of antigens to proteins

Phosphorylated peptide antigens (408LVRY*TKKVPQ417-AcA, where AcA stands for ε–amino caproic acid and * stands for a phosphonyl group were synthesized as described previously (MacDonald et al., 2010). The purity of each phosphorylated peptide-AcA was > 95% as judged by HPLC and the structure was confirmed by HPLC-MS. Each phosphorylated peptide-AcA was conjugated to keyhole limpet hemocyanin (KLH, Pierce, Rockford, IL) and chicken egg white ovalbumin (OVAL, Pierce) using ethyl-diisopropyl-carbodiimide (EDC) and sulfo N-hydroxysuccinimide (NHS) (1:1). Highly purified conjugated phosphorylated peptide-AcA-carrier protein was obtained after removing excess peptides and reagents by filtration and dialysis against phosphate buffered saline (PBS) buffer (pH 7.4) through repeated filtration with Amicon Ultra 4 centrifugation tubes (Millipore, Temecula, CA). Protein concentration was determined by a BCA assay (Pierce). The chemical stability of each antigen was tested by incubating the antigen at pH 7.4, room temperature and analyzing aliquots of the incubation
taken over time by mass spectrometry. All of the antigens examined possessed half life values greater than 8.5 days (Table 1). In the mass spectrometry experiment, we did not observe any new signals that may have indicated the loss of phosphonate or related groups from the antigens over the course of the stability tests.

Mouse immunizations

The procedures and care of animals used in this work conformed to the "Guiding Principles in the Care and Use of Animals" provided by the American Physiological Society, as well as all Federal and California regulations. HBRI has an approved Assurance from NIH's Office of Protection from Research Risks. Female Swiss Webster mice (5 weeks, 20 g) were purchased from Taconic Farms (Oxnard, CA) and used in immunization studies with the conjugated haptens. After one week of a stabilization period, 10 mice were immunized with each KLH-conjugated hapten (e.g., HSA-VX-KLH, HSA-GD-KLH, HSA-GF-KLH, HSA-GB-KLH or non-phosphonylated HSA-KLH). The immunization protocol consisted of an initial i.p. injection of 150 µg of conjugated hapten in 200 µl of an oil-in-water emulsion (PBS-containing Sigma Adjuvant System, Sigma, St. Louis, MI) followed by another boost four weeks later. After an additional three weeks each animal was boosted with 100 µg ovalbumin-conjugated phosphonylated HSA decapeptide (e.g., HSA-GD-OVAL, HSA-VX-OVAL, HSA-GF-OVAL, HSA-GB-OVAL) in 200 µl PBS-containing ALUM (Pierce) with an i.p. injection. Mouse blood (50-100 µl) was collected from each animal from the tail vein 7-10 days after each boost. Heparin (Sigma, 1-3 IU) was added to each blood sample, mixed thoroughly, and plasma was separated from blood cells through centrifugation at 5,000 x rpm for 10 min at 4ºC. Each plasma sample was tested for the presence of anti-phosphonylated peptide antibodies by ELISA (see
below). When the titer reached over 6,400 units, the mice were allowed to rest for at least 1 month. A final tail vein injection was made with KLH-conjugated phosphorylated peptides (25-50 µg in PBS) or non-phosphorylated HSA peptide conjugated KLH hapten 3 days before the mice were taken for splenectomy and cell fusion.

**Cell culture and fusions**

Mouse myeloma cells NS-1 (ATCC, Manassas, VA) were seeded at 50-100 x 10^3 cells/ml and grown in Medium A (Stem Cell Technologies, Vancouver, BC). Three days after the final tail vein immunization, mice were sacrificed and 1-2 x 10^8 isolated spleen cells were fused with 1-2 x 10^7 myeloma cells using polyethylene glycol (Stem Cell Technologies). After cell fusions, five 100 mm dishes were plated with 2-4 x 10^6 cells/ml in methycellulose medium (Medium D, Stem Cell Technologies) for 7-14 days. Single colonies of hybridoma cells were picked from methycellulose medium and cultured in Medium E (Stem Cell Technologies) in 96-well plates. Cell culture supernatants were tested for the presence of antibodies to ovalbumin-conjugated HSA-OP peptides (i.e., HSA-GB-OVAL, HSA-GD-OVAL, HSA-GF-OVAL, and HSA-VX-OVAL) or non-phosphorylated HSA-OVAL using ELISA. Positive cultures were expanded and supernatants were tested against a panel of antigens to verify antibody selectivity before secondary cloning in methycellulose Medium D or by limited dilution in Medium E. After recloning of hybridoma cells for 2-3 rounds, the monoclonal cells afforded single heavy chain and single light chain clones and were deemed clones that generated monoclonal antibodies and isotyped with isotyping kit (Pierce).

**Purification of antibodies**
For hybridoma cells expressing the desired anti-HSA-OP mAbs, the cell culture was expanded. Briefly, culture medium of the hybridoma cells was centrifuged at 1,000 rpm to separate cells from the supernatant and the supernatant was filtered to remove residual debris. To the culture medium supernatant was added 0.01% NaN₃ and mixed thoroughly at room temperature prior to purification. For mAb purification, the protein was dialyzed against PBS (pH 7.4) with 0.01% NaN₃ and mixed 1:1 with binding buffer (Pierce) and then chromatographed on Protein G Sepharose 4B (Sigma) equilibrated with PBS (pH 7.4) containing 0.01% NaN₃. Culture medium was loaded onto the column at 1 ml/min. The Protein G column was washed extensively with PBS (pH 7.4) containing 0.01% NaN₃. Bound antibodies were eluted with low-pH elution buffer (pH 2.0) (Pierce) and immediately neutralized to ~pH 7.5 with 1.0 M Tris. Protein-containing fractions were pooled based on OD₂₈₀ absorbance and dialyzed against PBS (pH 7.4) containing 0.01% NaN₃ for routine application. Purified antibodies were quantified by OD₂₈₀ absorbance (i.e., OD₂₈₀ 1.4 for 1 mg/ml IgG) and analyzed on SDS-PAGE for purity.

Western blot

Western blot analysis was conducted to determine levels of phosphonylated and non-phosphonylated OP-adducted serum albumin. The OP-adducted serum albumin was quantified in highly purified protein samples (or plasma protein samples) after removing cells by centrifugation at 5,000 rpm at room temperature for 10 minutes. Blood plasma protein samples were prepared by addition of a protease inhibitor cocktail (Sigma) in a 1:100 dilution containing 1 mM each of PMSF and Na₃VO₄, and 1 μg/ml each of aprotinin, leupeptin and pepstatin to the plasma. Samples were run on 10% SDS-polyacrylamide gels. The primary antibodies were obtained from hybridoma culture supernatant or highly purified mAbs. Secondary antibodies
used for Western blotting included HRP-conjugated goat anti-mouse antibodies (HRP-GAM) (Jackson ImmunoResearch Laboratories, Inc., West Grove, PA), and blots were developed using either SuperSignal West Pico chemiluminescent (Thermo Fisher, Waltham, MA) for regular detection or Immobilon Western Chemiluminescent HRP Substrate (Millipore, WBKLS0500) for high sensitivity detection. PVDF membranes were used in the experiment (Millipore, IPVH00010). For quantification, Western blots were scanned and densitometry was determined using Scion Image software (Scion Corporation, Frederick, MD).

**ELISA (enzyme linked immunosorbent assay)**

For quantification of immunoreactivity of serum from immunized mice or analysis of hapten binding of purified antibodies, ELISA was conducted. The wells of 96-well ELISA plates (Greiner, Neuburg, Germany) were coated with 0.1-2.0 μg of HSA-OP peptides or HSA-GB-OVAL, HSA-GD-OVAL, HSA-GF-OVAL, and HSA-VX-OVAL for 1 h at room temperature in 50 μl of PBS (without calcium or magnesium) at pH=7.4. After rinsing with PBST (PBS with 0.1% Tween-20), the 96 well plates were blocked for 1 h with 230 μl of blocking buffer (PBS containing 0.05% (v/v) Tween-20 (PBST) and 1% (w/v) bovine casein (Sigma) (PBSTC)). After removing the blocking buffer, 50-100 μl of hybridoma culture medium or purified antibody in PBSTC were applied to each well and allowed to incubate at 37°C in a CO₂ incubator for 1 h. After rinsing off the primary antibody, a 50 μl aliquot of HRP-GAM secondary antibody (1:4000 dilution in PBSTC) (Jackson Laboratories) was added to each well and incubated at room temperature for 1 h. After three rinses with PBST, bound antibody was detected by adding 100 μl of Pierce chemiluminescent substrate (Thermo Scientific, Brookfield, WI) to each well and reading the luminosity using a Wallac Victor² plate reader (PerkinElmer, Waltham, MA). For
evaluation of serum titers, plasma samples were diluted in PBSTC 1:100 fold and subsequently in 2-fold series. The diluted plasma assayed ranged generally from 1:100 to 1:128,000-fold dilutions depending on the titer.

**Preparation of rat blood plasma samples**

Male Sprague-Dawley rats (Crl:CD(SD); 250-300 g) were obtained from Charles River Laboratories (Wilmington, MA, USA). Rats were housed individually in polycarbonate cages in a temperature (21 ± 2 °C) and humidity (50 ± 10%) controlled colony room and maintained on a reversed 12-h light-dark cycle with lights off at 0900 h. Food and water were available *ad libitum* in home cages. Blood samples were obtained from nerve agent exposed animals as part of sample sharing from other studies conducted at the US Army Medical Research Institute of Chemical Defense. VX and soman were obtained from the US Army Edgewood Chemical Biological Center (Aberdeen Proving Ground, MD) and diluted in sterile saline. For VX, 0.8 LD50 (LD50 = 16 ug/kg) was administered subcutaneously into the right flank at a volume of 0.5 ml/kg body weight. For soman 132 ug/kg (1.2×LD50) was administered subcutaneously (0.5 ml/kg) followed 1 min later with co-administration intramuscularly (0.5 ml/kg) of the oxime HI-6 (93.6 mg/kg) and atropine sulfate (2 mg/kg). Diazepam (10 mg/kg) was administered subcutaneously 30 min after seizure onset. Standard therapy of an oxime, atropine and diazepam was given to maximize survival to a lethal dose of agent. Twenty-four hours after GD intoxication the rats were given a wet mash of food pellets and sugar. Subcutaneous injections of saline (3 ml) were administered as needed to prevent dehydration.

**Effect of Sp-GD on plasma ChE functional activity in rats**
From six 240 g male Sprague Dawley rats (Harlan, Milpitas, CA) administered 250 µg/kg of SpGD, tail vein blood was collected at different times, including 0, 2, 4, 6, 8, 24, 48, 72, 96, 144, and 240 hrs and immediately cooled to 4 ºC. Plasma was obtained from whole blood after separation by centrifugation at 2,000 x g for 10 minutes. Cholinesterase functional activity was detected by the Ellman assay (Ellman et al., 1961). Typically, 20 µl of plasma was used in each assay (1 mM acetylthiocholine, 1 mM DTNB in 50 mM PBS buffer, pH 7.4). Absorbance change of DTNB was monitored at 405 nm using a Cary UV-vis spectrophotometer. Absorbance at 405 nm versus time was plotted to obtain initial rate measurements. Initial rate measurements were normalized to zero time (i.e., before SpGD administration and was taken as 100% functional activity) and a plot of relative Cholinesterase activity versus hrs or days post-treatment was done with Graphpad Prism (San Diego, CA).

**Data analysis**

In the kinetic studies of antibody and ligand binding, the data analyses and statistical calculations were conducted with GraphPad Prism version 5.01 (GraphPad Inc., San Diego, CA).

**Results**

**Design and synthesis of antigens**

Although there are numerous reports concerning the synthesis of phosphorylated peptides (McMurray et al., 2001), before our publication (MacDonald et al., 2010), there were very few reports in the literature concerning the synthesis of phosphonylated peptides (Fidder et al., 2002). As previously described (MacDonald et al., 2010), four phosphonylated peptides were used in the synthesis of the required haptens (Figure 2), including peptide conjugates of sarin (GB) 1,
soman (GD) 2, cyclosarin (GF) 3 and VX 4. The chemical synthesis of the antigens and conjugated immunogens followed the general strategy described previously (MacDonald et al., 2010). Briefly, Fmoc-protected tyrosine, 5, was treated with monochloridates of nerve agent model compounds 1-4 to afford phosphorylated benzyl-protected Fmoc tyrosine 10-13, respectively (Figure 3). The monochloridates 1-4 were prepared as described before (MacDonald et al., 2010). After purification by chromatography on silica gel, the benzyl group was removed by hydrogenolysis. All of the compounds were fully characterized by \(^1\)H NMR and \(^{31}\)P NMR, mass spectrometry and HPLC. The phosphorylated products 10-13 were incorporated into solid phase peptide synthesis to afford the desired phosphorylated peptide 14-17 containing an aminocaproic acid at the carboxyl terminus. These products were >95% pure on the basis of HPLC and mass spectrometry. The carrier protein KLH was conjugated through the aminocaproic acid to produce the desired conjugated hapten-KLHs that were used to immunize mice (Figure 3). Alternatively, 14-17 was used to conjugate to ovalbumin or HSA that were used in various bioassays. In total, three different phosphorylated peptide conjugates were synthesized (i.e., hapten-KLH, hapten-HSA and hapten-ovalbumin) for GB, GD, GF and VX. In addition, non-phosphorylated peptide conjugates (i.e., peptide-KLH, peptide-HSA and peptide-ovalbumin) were prepared and characterized. Characterization of the HSA-phosphorylated-peptide-aminocaproic acids was summarized in Table 1. Because of the potential chemical lability of haptens 14-17, chemical stability studies were conducted. As shown in Table 1, on the basis of mass spectrometric studies of the kinetics of loss in the presence of potassium phosphate buffer (pH 7.4), the haptens possessed considerable chemical stability. Loss of
material may have been to adherence to plasticware or other surfaces because no detectable degradation products were observed as judged by mass spectrometry.

**Procurement of antibodies**

Tail vein blood was obtained from the immunized mice and plasma obtained after centrifugation was tested for the presence of anti-phosphorylated HSA-peptide (i.e., anti-GB-, GD-, GF- and VX-HSA antibodies) by ELISA. When the titer reached over 6,400 units, the mice were allowed to rest at least 1 month. A final tail vein injection was made with KLH-conjugated phosphorylated peptides before splenectomy and cell fusion. Spleens from immunized mice were obtained and finely minced for fusion with myeloma cells to give rise to primary hybridoma cells. Fusion of spleens from mice immunized against GB and GF yielded very few primary hybridomas and thus, we focused our efforts on hybridoma cells from F41 and F46 (i.e., hybridomas that produced monoclonal antibodies that selectively recognized HSA-GD and HSA-VX, respectively, named mAb41.5D5A2 and mAb46.5H10G7). After screening >200,000 primary cells, 40 clones were obtained. Recloning of these 40 positive hybridoma cells 2-3 more times provided homogenous cell lines expressing two lines of monoclonal antibodies (mAbs) that selectively recognized HSA-GD or HSA-VX. Thus, mAb-HSA-GD and mAb-HSA-VX, were obtained after cloning and recloning several generations of hybridoma cells. The mAbs were purified to homogeneity and characterized by SDS-PAGE and isotyping (Figure 4). The isotypes for both mAb-HSA-GD and mAb-HSA-VX were determined to be IgG1b and their light chains were both kappa isotype.

**In vitro characterization of mAb-HSA-GD and mAb-HSA-VX**
Characterization of the selectivity of mAb-HSA-GD and mAb-HSA-VX was done using four different peptide haptens (i.e., HSA-GD, HSA-VX, HSA-GB, and HSA-GF) that were chemically synthesized to afford the same phosphonyl adduct as the actual nerve agents (Figure 3). The non-phosphonylated decapeptide (i.e., HSA-NP) was also prepared and used for comparison. As shown in Figure 5, ELISA data showed that mAb-HSA-GD had the greatest affinity for HSA-GD, while mAb-HSA-VX had the greatest affinity for HSA-VX. Compared to other mAbs obtained, Ab-HSA-GD showed selective recognition of HSA-GD and HSA-GF and to a much lesser extent the other HSA-OP adducts (i.e., GD ~ GF >> GB > VX). mAb-HSA-GD did not recognize the HSA peptide that did not contain a phosphonyl group on Tyr 411 (i.e., HSA-NP). mAb-HSA-VX selectively recognized HSA-VX compared to the other HSA-OP peptide adducts (i.e., VX >> GB > GF > GD). mAb-HSA-VX did not recognize the HSA peptide that did not contain a phosphonyl group (i.e., HSA-NP). The \( K_d \) values for mAb-HSA-GD and mAb-HSA-VX was 30 nM and 0.4 nM, respectively (Figure 5). The affinity of mAb-HSA-GD for HSA-GD or mAb-HSA-VX for HSA-VX, respectively, was confirmed with Western blot studies. As shown in Figure 6, the immunoreactivity of mAb-HSA-GD for HSA-GD was greater than HSA-GB~HSA-GF >> HSA-VX. No significant immunoreactive signal was observed for mAb-HSA-GD against HSA-GA (HSA-tabun) or HSA-NP at low immunogen levels.

In good agreement with the ELISA data, on the basis of Western blot analysis, the immunoreactivity of mAb-HSA-VX was HSA-VX >> HSA-GB > HSA-GF. No significant immunoreactive signal was observed for mAb-HSA-VX against HSA-GD, HSA-GA or HSA-NP at low immunogen levels. The affinities of mAb-HSA-VX and mAb-HSA-GD suggested that the antibodies could have utility in the selective analysis of exposure to different nerve agent OPs.
because the two antibodies readily detected GD and VX, respectively, and to a lesser extent, GB and GF.

Because the antibodies were designed to be used in detection and analysis of OP exposure in vivo, we sought to increase the sensitivity of detection and develop a robust method to detect OPs at very low concentrations. To test the lowest level of detection of the antibodies, we conducted a titration experiment by serially diluting an authentic HSA-GD protein standard. Previously, the amount of phosphonylated HSA Tyr 411 adducted with GD had been determined by tryptic digestion and liquid-chromatography-mass spectrometry (LC-MS) studies and was available as a standard (Li et al., 2007) (O. Lockridge, personal communication). An HSA-VX standard protein was not available so the study was largely conducted with mAb-HSA-GD. As shown in Figure 7B, the lowest level of detection of the GD adduct on Tyr 411 of HSA was on the order of $10^{-12}$ g with a femtogram sensitive HRP substrate in a Western blot analysis format.

Because mAb-HSA-GD showed superb sensitivity in detecting GD-adducted HSA on the basis of serially diluted standard protein samples in PBS, we extended the studies to detection of OP-adducted serum albumin isolated from animal blood samples. Because it was estimated that only 1-2% of serum albumin would form Tyr 411 adducts during OP exposure (Ding et al., 2008), in order to recognize the serum albumin-GD adduct in blood plasma, it was required that the antibody not only have the ability to detect low levels of target protein as shown in Figure 7, but also have the ability to distinguish serum albumin-soman adduct in the presence of large quantities of unmodified serum albumin. We therefore conducted experiments to simulate these conditions in blood plasma before embarking on more complex detection in blood samples from animals exposed to OPs. In these experiments, OP-adducted HSA standards previously
quantified by LCMS (O. Lockridge, personal communication,) were serially diluted in the presence of unmodified HSA. The total protein in each dilution experiment was 1 mg, as shown by Ponceau staining in Figure 7C. When an HSA solution was used in a serial dilution experiment, compared to dilution in PBS, the intensity of the signal was not significantly decreased (e.g., Figures 7B and 7C), and the antibody recognized far less than 1% of a theoretical amount of HSA-soman adduct in solution. For example, in an experiment with 1.6 % of the serum albumin adducted with GD (determined by mass spectrometry after tryptic digestion) at a typical blood plasma concentration, the mAb-HSA-GD readily recognized HSA-soman adduct (i.e., the second lane of Figure 7B represented a typical blood plasma that had 1-2% of HSA-soman adduct). Thus, using the methodology developed, detection of very low levels of HSA-adducted OPs was feasible even in the presence of large amounts of unmodified HSA.

**Phosphonylation of HSA in the presence of para-nitrophenyl esters of nerve agents**

To study the kinetics of OP adduction of HSA *in vitro*, we synthesized para-nitrophenyl esters of nerve agent model compounds 18, 19 and 20 (Figure 8). The *para*-nitrophenol (pNP) leaving group of these OP esters liberated when the *para*-nitrophenyl esters covalently modified HSA was continuously monitored at 400 nm. From the time course studies the half life of adduction of HSA by GB, GD, and VX model compounds 18-20 were 6.1 ± 4, 10.9 ± 5, and 16.4 ± 9 hours, respectively (Table 2).

**Stereoselectivity of antibody mAb-HSA-GD**
Certain nerve agents and other OPs have a center of chirality about phosphorous. Generally, authentic nerve agents are present as racemic mixtures. However, work has been done with enantiomerically pure nerve agents (Benschop and De, 1988) and nerve agent model compounds (Zheng et al., 2010). It has been observed that nerve agent or nerve agent model compound enantiomers inhibit cholinesterase with considerable stereoselectivity (i.e., cholinesterase inhibition is: \(Sp\) nerve agent > \(Rp\) nerve agent) (Benschop and De, 1988; Zheng et al., 2010). The observations from \textit{in vitro} cholinesterase inhibition studies are relevant to \textit{in vivo} toxicity because it has been shown that nerve agents or nerve agent model compounds with \(Sp\) chirality are much more toxic than nerve agents with \(Rp\) chirality (Benschop and De, 1988; Kalisiak et al., 2011; Kalisiak et al., 2012).

As a model system to test the ability of mAb-HSA-GD to recognize different optical isomers of HSA-GD adducted to HSA, we examined the stereoselectivity of mAb-HSA-GD recognition of the adduct of \(Rp\) and \(Sp\) GD model compound enantiomers \textit{in vitro}. Previously, we showed that several nerve agent model compounds recapitulated the stereoselectivity and mechanism of action of actual nerve agents in all respects except the model compounds were less toxic (Gilley et al., 2009). Accordingly, we incubated \(Rp\)-GD methylthiocholine or \(Sp\)-GD methylthiocholine (0.2 mg/ml) in the presence of HSA (60 mg/ml) over a 20 day time course to examine if GD adducts could form, and if the adduct formed was stable. We also examined the stereoselectivity of the adduction. Over the course of a 20 day incubation, based on the area of the product formation curves, \(Sp\)-GD methylthiocholine showed approximately a 1.3-fold greater stereoselectivity in HSA adduct formation recognition by mAb-HSA-GD compared with the amount of adduct formed from \(Rp\)-GD in the \textit{in vitro} system (Figure 9). While the total amount
of OP adduct recognized by the mAb-HSA-GD was significantly different for each OP enantiomer, the stability of the adducts appeared to be similar.

**Immunodetection of GD in human blood plasma samples**

As described above, we characterized mAb-HSA-GD and mAb-HSA-VX with highly purified OP-adducted HSA samples *in vitro*. mAb-HSA-GD was characterized for its ability to recognize nerve agent-adducted HSA in the presence of HSA. We next examined if mAb-HSA-GD could recognize authentic HSA-adducted GD standards in the presence of human blood plasma. As shown in Figure 10, mAb-HSA-GD detected extremely low levels of HSA-GD in the presence of human plasma that was treated with 0.18 µM GD for 72 hours. Under similar conditions, no detectable amount of OP adduct could be detected by LCMS under standard tryptic digestion and analysis conditions (O. Lockridge, personal communication). After analysis by densitometry, the level of HSA-GD detected in human plasma treated with 0.18 µM GD was determined to be 0.1 ng/ml using an HSA-GD protein standard as a positive control.

**Immunodetection of GD adducts in rat serum albumin from plasma of rats administered GD**

We examined if mAb-HSA-GD could detect GD-adducted albumin in the presence of blood samples from animals treated with authentic nerve agents. Rat blood plasma samples were prepared from rats 72 hours after the animals had been administered GD subcutaneously at 1.2-fold the LD₅₀ for GD. As shown in Figure 11, four different samples from plasma isolated from the blood of rats treated with GD (lanes 2, 3, 5, and 6) showed immunoreactive bands for GD-rat serum albumin (i.e., RSA-GD) with mAb-HSA-GD on the basis of Western blot analysis.
Samples that showed no OP-adducted RSA signal (lanes 1, 4) were derived from rats that were treated with PBS. Purified rat serum albumin and HSA were used as negative control samples in the same Western blot analysis (lanes 7, 8). The positive control samples used in characterization of mAb-HSA-GD in vitro (Figure 7) were also used as positive controls in the Western blot and a quantification standard (lane 9). The results showed that mAb-HSA-GD was suitable for low level detection and sensitive analysis of authentic biological samples of GD-adducted blood from rats. The RSA-GD detected was quantified by densitometry using HSA-GD as a standard to be 5.4 ± 1.1 ng/ml plasma.

**Immunodetection of VX adducted to rat serum albumin from plasma of rats administered VX**

We examined the plasma isolated from rats administered authentic VX with mAb-HSA-VX to detect VX-adducted serum albumin. In a similar fashion to the detection of GD-adducted RSA from rats administered GD described above, VX-adducted RSA was detected in plasma samples from rats treated with authentic VX. As shown in Figure 12, blood plasma samples isolated from rats 72 hours after administration of VX subcutaneously at 0.8-fold the LD$_{50}$ showed immunoreactive RSA-VX adducts. The selective immunodetection showed that VX-adducted on Tyr 411 of RSA was detectable even at sublethal doses. The RSA-VX detected was quantified by densitometry using HSA-GD as a standard and was observed to be 5-50 ng/ml (quantification was done by comparing the VX band intensity in the Western blot with HSA-GD band on the same blot because no independently verified HSA-VX was available).
In addition to GD and VX detected in RSA from rats administered the actual nerve agents, mAb-HSA-GD was able to detect GD-adducted serum albumin in the presence of plasma 30 minutes after African green monkeys were administered authentic GD (15 µg/kg). In addition, mAb-HSA-VX immunodetected VX-adducted serum albumin from the plasma of guinea pigs 72 hours after administration of an 0.6-0.8 LD₅₀ of VX (subcutaneous injection) (Supplemental Figure 1). The immunodetection of GD adducted to monkey serum albumin under these conditions was determined to be 1.8 ± 0.4 ng/ml plasma.

**Cholinesterase activity inhibition by GD model compound**

One of the acute toxic effects of nerve agents is the cholinesterase inhibition in the blood. We therefore investigated the time course of cholinesterase inhibition with a GD model compound RpGD tertiary amine (Barakat et al., 2009) and compared it to one reported for GD. As shown in Figure 13A, 80% of the functional activity of cholinesterase in rat blood plasma was inhibited by SpGD model compound at the 4-hr time point, but fully recovered to normal level after 48 hrs. At the 72-hr point, the cholinesterase activity was completely recovered to a normal level (Figure 13B) while RSA-GD was still readily detectable (Figure 11). Comparison of data for GD (i.e., 0-24 hr, (Geller et al., 1987) and up to 10 days (Jovic, 1974), with the RpGD model compound showed similar results in inhibition of cholinesterase functional activity (Figure 13).

**Discussion**

Herein we describe the characterization of nerve agent- or nerve agent model compound-adducted serum albumin from large and small animals using monoclonal antibodies raised against nerve agent-phosphonylated peptides of HSA. As shown in Figure 13, nerve agent
model compounds showed a similar time course of action compared to the actual nerve agent (i.e., Sp-GD vs. GD itself) albeit at different doses. Consequently, data using nerve agent model compounds provide a useful approach in advance of studies using the actual nerve agents. The monoclonal antibodies obtained showed remarkable sensitivity and selectivity in detecting phosphorylated serum albumin from both in vitro and in vivo samples. As shown in Figures 7A and B, in the case of in vitro samples, mAb-HSA-GD was able to recognize as low as 100 pg of HSA-GD. In contrast, detection of tryptic digests of a similar sample has a limit of detection of 250 ng (Ding et al., 2008). The monoclonal antibodies described herein are remarkably selective and can distinguish phosphorylated HSA from non-phosphorylated HSA. Even minor structural changes of nerve agent-HSA adducts could be distinguished. As shown in Figure 7B, mAb-HSA-GD was able to recognize HSA-GD in the presence of non-phosphorylated HSA as low as a 2^{13}:1 molar ratio dilution without losing any sensitivity (i.e., compared to identical fold-dilutions in the presence of PBS or HSA solution). In the case of in vivo samples, mAb-HSA-GD was capable of detecting exposure to nerve agent model compounds or actual nerve agents from biological samples at extremely low levels that were not detectable by mass spectrometric methods (Figure 10 and personal communication, O. Lockridge). Animals treated with nerve agents (i.e., GD or VX) at sublethal doses afforded plasma that showed immunoreactivity to the corresponding adduct at Tyr 411 of serum albumin.

Currently available approaches for the detection of OP exposure including functional enzyme assays and MS-based approaches have certain advantages and drawbacks (Worek et al., 2005; Thompson et al., 2010). For example, assay of functional activity of AChE and BChE are quick and efficient but do not provide information about the type of nerve agent that is present and
inhibiting the enzyme. MS-based approaches to detect protein adducts of OPs are quite sensitive but require expensive equipment and well-trained operators (Worek et al., 2005). The approach described herein employs a biological method using immunodetection that is efficient and robust.

Nerve agent adducts of serum albumin was chosen to develop immunodetection because previous studies of BChE showed the phosphorylated peptide surrounding the active site serine of BChE is prone to elimination and affords the corresponding dehydroalanine-containing peptide (Masson and Lockridge, 2009). The phosphorylated peptide that corresponds to the region surrounding Tyr 411 of HSA shows significant stablility and the adduct is not prone to elimination (Masson and Lockridge, 2009). The antibodies described herein, mAb-HSA-GD and mAb-HSA-VX, can distinguish phosphorylated Tyr 411 peptides from non-phosphonylated peptides. In particular, the antibodies selectively recognized phosphorylated Tyr 411 on serum albumin, (i.e., anti-HSA-GD recognizes GD-adducted HSA at Tyr 411 and anti-HSA-VX selectively recognizes VX-adducted HSA at Tyr 411) in Western blot analysis. To our knowledge, these antibodies are the first antibodies that can selectively recognize defined phosphorylated peptides of protein samples from in vivo serum samples.

The specificity of the antibodies reported herein was achieved using a defined epitope approach to raise antibodies that could distinguish native and phosphorylated peptide. Previously, a report showed antibodies could distinguish phosphorylated AChE and inhibited AChE using this strategy (George et al., 2003) but despite their utility, these polyclonal anti-phosphorylated AChE antibodies did not have the ability to distinguish different OP-adducts. The results of that
report did suggest that it was possible to raise antibodies to individually recognize specific modifications of the dianionic phosphorus of OP-adducted proteins (George et al., 2003).

Another strategy reported in the literature to raise antibodies to selectively recognize OPs is to raise antibodies against different epitopes of the same hapten (26). Although antibodies raised against OPs following this strategy did bind to different OP-adducts with some affinity, their binding to the desired OP-adducted protein was reportedly relatively weak and not selective because most of the antibodies described had IC$_{50}$ values to their desired antigen in the range of 10$^{-4}$-10$^{-6}$ M (Hunter and Lenz, 1982; Hunter et al., 1982; Hunter et al., 1985; Hunter et al., 1990; Brimfield et al., 1993; Johnson et al., 2005). For example, antibodies raised against soman that was conjugated to the carrier protein BSA had an IC$_{50}$ value of 10$^{-4}$ M to its antigen (Lenz et al., 1992). Antibodies raised against soman that were conjugated to carrier protein KLH had a reported IC$_{50}$ value of 10$^{-6}$ M to its antigen (Hunter and Lenz, 1982). Compared to the monoclonal antibodies described herein, the previously reported antibodies to phosphorylated haptens may be useful in qualitative analysis of biomedical samples, but may have less utility in quantitative studies.

Using a defined epitope approach, mAb-HSA-GD and mAb-HSA-VX, described herein, showed excellent detection of phosphorylated serum albumin using Western blot analysis across different species. The cross-species detection is undoubtedly due to the conserved nature of the region in the serum albumin protein sequence used in the hapten.

After being exposed to nerve agents, there are numerous protein-OP adducts formed in the blood, including cholinesterases and serum albumin. As shown in Figure 13, following nerve agent
model compound or actual nerve agent administration, rat cholinesterase functional activity is largely abrogated at 24 hours but functional activity is recovered to normal levels after 48 hours. Therefore, cholinesterase functional activity can be used as a biomarker in OP poisoning in the short term, but cholinesterase functional activity cannot be reliably used as a biomarker for OP exposure much beyond 48 hrs. In contrast, serum albumin - GD-adducts from animals exposed to nerve agents were still readily detectable by mAb-HSA-GD 72 hrs after exposure well after cholinesterase functional activity recovered back to normal levels. This data shows that the detection of HSA-GD is a more robust biomarker than cholinesterase functional activity at longer time points post-administration. The availability of mAbs described herein also affords detection of nerve agent-adducted serum albumin and provide structural information to identify the chemical nature of the agent possibly long after the subject has been exposed to a nerve agent. In fact, some of the samples used in the studies described herein had been stored at -80 °C for 3 years.

It is known that soman contains two centers of chirality. Although it has been reported that stereoisomers of soman have differential effects on their toxic potency in vivo, the potency of each isomer has largely been studied in detail for stereoselectivity of cholinesterase inhibition (Benschop and De, 1988). Little has been reported about the reaction of soman stereoisomers with serum albumin. As shown in Figure 9, mAb-HSA-GD stereoselectively recognized the SpGD isomer in preference to the RpGD isomer adducted to HSA. The result may suggest that SpGD more avidly binds to HSA compared to the RpGD isomer or it may suggest that the mAb-HSA-GD stereoselectively distinguishes GD-serum albumin adducts. If the nerve agent model compounds recapitulate the action of actual nerve agents (albeit at greater doses), the observation
regarding stereoselective GD-serum albumin adduction may have some consequences for deconvoluting the mechanism of toxicity of soman (and other nerve agents). In conclusion, using a defined epitope approach, we obtained two monoclonal antibodies that selectively recognize GD- or VX-adducted HSA at Tyr 411. The two monoclonal antibodies showed unprecedented sensitivity and selectivity in detection of nerve agent biomarkers both in vitro and in vivo. The monoclonal antibody approach presented herein provides a powerful tool in the detection of biomarkers for nerve agent OP detection.

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We are grateful to Dr. Oksana Lockridge (University of Nebraska Medical School) for providing the human serum albumin-soman adduct that were used as independently verified protein standards. We sincerely thank Dr. John McDonough (U.S. Army Medical Research Institute of Chemical Defense, Aberdeen Proving Ground, MD) for providing monkey blood plasma samples. We also thank Don Kaiser for the work on hybridoma cells and monoclonal antibody screening. We thank Drs. Mary MacDonald and Marion Lanier for chemical synthesis of the haptens and immunogens.

**Authorship contributions**

*Participated in research design:* Chen, Zhang and Cashman.

*Conducted experiments:* Chen, Zhang and Cashman.

*Contributed new reagents or analytic tools:* Lumley.

*Performed data analysis:* Chen, Zhang and Cashman.

*Wrote or contributed to the writing of the manuscript:* Chen, Zhang, Lumley and Cashman.
REFERENCES


Footnotes

1Both authors made complementary and equal contributions to the manuscript.

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Figure Legends

Figure 1. A comparison of the peptide sequence of serum albumin in the epitope region surrounding Tyr 411 for four species including human serum albumin (HSA), monkey serum albumin (MSA), guinea pig serum albumin (GSA), and rat serum albumin (RSA).

Figure 2. Chemical structures of the monochloridates of nerve agent model compounds used in the synthesis of haptens. A. GB, B. GD, C. GF, and D. VX.

Figure 3. Chemical synthesis of phosphonylated peptides conjugated to KLH via amino caproic acid (AcA) used to generate monoclonal antibodies that recognize nerve agents adducted to serum albumin. A. The monochloridates of model compounds of sarin, soman, cyclosarin, and VX (i.e., compounds 1-4) were treated with with Fmoc- and benzyl-protected tyrosine (compound 1) to afford 6-9. B. After benzyl deprotection the resulting carboxylic acids (i.e., compounds 10-13) were used in solid-phase peptide synthesis to make the phosphonylated peptide-AcA. C. Solid-phase peptide synthesis using Fmoc-protected phosphonylated tyrosine. D. The resulting haptens (14-17) were conjugated to keyhole limpet cyanin (KLH) to form the antigen. E. The conjugated antigen was used to immunize mice to generate antibodies.

Figure 4. SDS-PAGE of monoclonal antibodies. Lane 1: monoclonal antibody mAb-HSA-GD. Lane 2: monoclonal antibody mAb-HSA-VX.

Figure 5. Characterization of antibodies by competitive ELISA with synthetic phosphonylated and non-phosphonylated peptides attached to ovalbumin (i.e., HSA-GB-OVAL, HSA-GD-OVAL, HSA-GF-OVAL, and HSA-VX-OVAL and non-phosphonylated HSA-NP-OVAL). HSA-NP is the non-phosphonylated peptide (NP). A. Monoclonal antibody
mAb-HSA-GD. B. Monoclonal antibody mAb-HSA-VX. (▼) HSA-VX; (□); HSA-GD; (△)
HSA-GF; (◯) HSA-GB; (◇) HSA-NP. RU, Relative Luminescence Units. Experiments were
carried out with 1:100 diluted hydridoma cell culture medium. Monoclonal antibody was pre-
incubated separately with each phosphorylated or non-phosphorylated HSA-peptide as
described in the Methods. The bound antibody was measured indirectly using a HRP-conjugate
secondary antibody.

Figure 6. Western blot analysis of haptens conjugated to ovalbumin (i.e., HSA-GB-OVAL,
HSA-GD-OVAL, HSA-GA-OVAL, HSA-GF-OVAL, and HSA-VX-OVAL and non-
phosphonylated HSA-NP-OVAL). HSA-NP is the non-phosphonylated peptide (NP). mAb-
HSA-GD (A) or mAb-HSA-VX (B) were tested for their preferential binding to the haptens
(above) by Western blot analysis.

Figure 7. Determination of limit of detection by mAb-HSA-GD for HSA-soman protein
adduct. A. Detection of HSA-soman protein adduct with a low-sensitivity chemiluminescent
HRP substrate. B. Detection of HSA-soman protein adduct with a high- sensitivity HRP
substrate. C. Ponceau staining of membranes used in A and B shows the relative protein content
using a Western blot on a PVDF membrane. In the experiment, 1 µg of HSA-soman protein
adduct standard (containing 21% of the Tyr-411 amino acid adducted as HSA-soman,
independently pre-determined by mass spectrometry) was serially diluted (as indicated by the
fold-dilution on the top of the blot) in either PBS or HSA solution (containing 1 mg/ml of
unmodified HSA in each lane).
Figure 8. Chemical structure of para-nitrophenyl esters of nerve agent as photometric model compounds. A. Structure of para-nitrophenyl-GB. B. Structure of para-nitrophenyl-GD. C. Structure of para-nitrophenyl-VX.

Figure 9. A plot of the amount of soman nerve agent model compound stereoisomers adducted to HSA as a function of time based on quantification of immunoreactivity with mAb-HSA-GD. The amount of HSA-soman protein adduct was determined by Western blot analysis. After addition of nerve agent model compound $Sp$-GD or $Rp$-GD methylthiocholine to HSA, the incubation was sampled over time and compared with a HSA-soman adducted protein standard. Quantification was done by densitometry. (◯) $Sp$-GD methylthiocholine; (□) $Sp$-GD methylthiocholine.

Figure 10. Western blot analysis of human blood plasma samples treated with soman. Top panel, Western blot of human blood plasma samples treated with soman (0.18 µM) for 72 hrs and probed with mAb-HSA-GD. Lower Panel. Ponceau staining of the PVDF membrane used in the Western blot shows an equal amount of serum albumin. Lane 1, untreated human plasma (1 µl); Lane 2, human plasma (1 µl) treated with 0.18 µM soman; Lane 3, positive control protein HSA-soman adducted protein standard (1 µg).

Figure 11. Western blot using mAb-HSA-GD of plasma samples from rats treated with soman (1.2 x LD$_{50}$) for 72 hrs. A. Lanes 1 and 4, plasma (1 µl) from untreated rats; Lanes 2, 3, 5 and 6, plasma from rats treated with soman; Lane 7, untreated rat serum albumin (1 µg); Lane 8, HSA (1 µg); Lane 9, A standard of 1 ug of soman-adducted HAD (independently...
characterized by mass spectrometry. B. Coomassie blue staining of an identical gel as blot A run in parallel that showed equal protein loading of serum albumin.

Figure 12. Western blot using mAb-HSA-VX of plasma samples from rats treated with VX (0.8 x LD_{50}) for 72 hrs. A. Lanes 1 and 3, plasma (1 µl) from untreated rats; Lane 2 and 4, plasma (1 µl) from treated rats. B. Ponceau staining of an identical gel as blot A run in parallel that showed equal protein loading of serum albumin.

Figure 13. Time course for inhibition of rat plasma cholinesterase functional activity by nerve agent model compound SpGD tertiary amine (Barakat et al., 2009) or soman after administration to rats. A. Comparison of inhibition of rat plasma cholinesterase by nerve agent model compound SpGD (□) (250 µg/kg, i.p.) and soman (◯) (88 µg/kg, i.p) modified from (Geller et al., 1987). B. Comparison of time course (0-10 days) for inhibition of rat plasma cholinesterase activity by nerve agent model compound SpGD tertiary amine (250 µg/kg, i.p.) (□) (Barakat et al., 2009) and soman (◯) 25.5 µg/kg, i.p) modified from (Jovic, 1974).
Table 1. Characterization of phosphonylated peptide-amino caproic acid hapten purity and aqueous stability.

<table>
<thead>
<tr>
<th>Name</th>
<th>T_{1/2} (days)^1</th>
<th>MW</th>
<th>Purity^2</th>
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<tbody>
<tr>
<td>HSA-peptide-AcA-GB</td>
<td>12.0</td>
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<td>&gt;92.4%</td>
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<tr>
<td>HSA-peptide-AcA-GD</td>
<td>16.3</td>
<td>1507.4</td>
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</tr>
<tr>
<td>HSA-peptide-AcA-GF</td>
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<td>1505.3</td>
<td>&gt;99.2%</td>
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<tr>
<td>HSA-peptide-AcA-VX</td>
<td>8.5</td>
<td>1451.3</td>
<td>&gt;98.4%</td>
</tr>
</tbody>
</table>

^1Peptide half life was determined by mass spectrometric analysis (deionized H₂O, 25 °C).

^2Organophosphate-adducted peptide purity was determined by HPLC.
Table 2. Half life values and kinetic constants for the pseudo first order reaction between nerve agent model compound \textit{para}-nitrophenyl esters 10-12 and HSA.

<table>
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<tr>
<th>Nerve agent model compound</th>
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<th>$k$ (hr)$^{-1}$</th>
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<tr>
<td>\textit{para}-nitrophenyl-GB 10</td>
<td>10.9±5</td>
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</tr>
<tr>
<td>\textit{para}-nitrophenyl-GD 11</td>
<td>6.1±4</td>
<td>0.11±0.07</td>
</tr>
<tr>
<td>\textit{para}-nitrophenyl-VX 12</td>
<td>16.4±9</td>
<td>0.04±0.02</td>
</tr>
</tbody>
</table>

$^1$ Experiments were carried out at pH 7.4, room temperature.
Figure 1

Consensus

HSA
MSA
GSA
RSA
Figure 3
Figure 6

A. HSA-NP-OVAL  HSA-GA-OVAL  HSA-GB-OVAL  HSA-GD-OVAL  HSA-GF-OVAL  HSA-VX-OVAL

B. HSA-NP-OVAL  HSA-GA-OVAL  HSA-GB-OVAL  HSA-GD-OVAL  HSA-GF-OVAL  HSA-VX-OVAL

98 KD
67 KD
Figure 7

A. Low Sensitivity

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<th>0.5^9</th>
<th>0.5^10</th>
<th>0.5^11</th>
<th>(µg dilution)</th>
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HSA-soman protein adduct in PBS

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<th>0.5^5</th>
<th>0.5^6</th>
<th>0.5^7</th>
<th>(dilution)</th>
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</table>

HSA-soman protein adduct in HSA solution

B. High Sensitivity

<table>
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<th>0.5^8</th>
<th>0.5^9</th>
<th>0.5^10</th>
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<th>0.5^12</th>
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<th>(µg dilution)</th>
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HSA-soman protein adduct in PBS

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<th>0.5^5</th>
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<th>0.5^12</th>
<th>0.5^13</th>
<th>(µg dilution)</th>
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</thead>
</table>

HSA-soman protein adduct in HSA solution

C. Ponceau

HSA-soman protein adduct in PBS

HSA-soman protein adduct in HSA solution
Figure 8

A.  

B.  

C.  

18  

19  

20
Figure 9

Immunodetection (ng)

0 5 10 15 20 25

Time (Days)
Figure 11

Western Blot

Coomassie Blue Staining
Figure 13.

A. Percent ChE Activity

B. Percent ChE Activity