Stimulation of central A1 adenosine receptors suppresses seizure and neuropathology in a soman nerve agent seizure rat model

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14. ABSTRACT
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15. SUBJECT TERMS
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Stimulation of central A1 adenosine receptors suppresses seizure and neuropathology in a soman nerve agent seizure rat model

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Abstract
The current regimen for treating nerve agent poisoning does not sufficiently suppress the excitotoxic activity that causes severe brain damage, especially in cases where treatment is delayed and nerve agent-induced status epilepticus develops. New therapeutic targets are required to improve survivability and minimize neuropathology after irreversible acetylcholinesterase inactivation. Earlier studies have shown that systemic delivery of adenosine agonists decreases nerve agent lethality; however, the mechanism of protection remains to be understood. The primary aim of this study was to investigate the role of central adenosine receptor (AR) stimulation in neuroprotection by directly injecting (6)-cyclopentyladenosine (CPA), an adenosine agonist specific to the A1 receptor subtype (A1R), into the brain intracerebroventricularly (ICV) in a soman seizure rat model. In addition to general A1R stimulation, we hypothesized that bilateral micro-injection of CPA into the cholinergic basal forebrain (BF) could also suppress excitotoxic activity. The results from these studies demonstrated that centrally administered adenosine agonists are anti-seizure and neuroprotective. CPA-delivered ICV prevented seizure and convulsion in 100% of the animals. Moreover, neuropathological evaluation indicated that adenosine treatments reduced brain damage from severe to minimal. Inhibition of the BF via CPA had varied results. Some animals were protected by treatment; however, others displayed similar pathology to the control. Overall, these data suggest that stimulating central ARs could be an effective target for the next generation countermeasures for nerve agent intoxication.

Keywords
Adenosine agonist, anti-seizure, nerve agent, neuroprotection

Introduction
Organophosphorus (OP) chemical warfare nerve agents (CWNAs), such as soman and sarin, irreversibly inhibit acetylcholinesterase (AChE), the enzyme responsible for hydrolyzing the neurotransmitter acetylcholine (ACh) in the cholinergic synapses and neuromuscular junctions (McDonough & Shih, 1997). Following exposure to CWNAs, the earliest neurochemical events detectable in the central nervous system (CNS) are the inhibition of AChE and an immediate increase in brain neurotransmitter acetylcholine (ACh) levels (Shih, 1982). After a longer duration of seizure activity, changes in the levels of excitatory (glutamate) and inhibitory (γ-aminobutyric acid, GABA) amino acid transmitters are observed (el-Etri et al., 1992; Fosbraey et al., 1990; Lallement et al., 1991; O’Donnell et al., 2010, 2011; Wade et al., 1987). Many potential inhibitory compounds and drugs along these lines of neurotransmission perturbations have been investigated (McDonough & Shih, 1997; Shih, 1990; Shih et al., 2003). These treatments have limited efficacy in protecting the CNS, particularly in cases of prolonged seizure activity. Therefore, investigation and exploration of new therapeutic targets for CWNA countermeasures are needed.

Adenosine is an endogenous substance that regulates multiple peripheral and central physiologic functions. It is released during normal metabolic activity into the extracellular space where it acts on adenosine receptors (ARs) (Ribeiro et al., 2002). Adenosine modulates cellular activity by stimulating specific AR subtypes that are classified according to their effect on adenylyl cyclase; A1 inhibits activity via Gz proteins (Haas & Selbach, 2000; Sperlagh & Vizi, 2011; St Hilaire et al., 2009). Adenosine’s most notable physiologic effect occurs with the stimulation of A1Rs in the brain. Activation of central A1Rs elicits a profound inhibitory effect on neuronal excitability and synaptic transmission.
Pre-synaptically, adenosine reduces the influx of calcium, which suppresses the release of glutamate. Post-synaptically, adenosine decreases neuronal excitability by inhibiting \( N \)-methyl-\( D \)-aspartate (NMDA) receptors and voltage-sensitive calcium channels (Malva et al., 2003; Ribeiro et al., 2002). A1Rs are distributed throughout numerous brain structures including the cortex and thalamus, and have the highest densities in critical cholinergic centers, such as the basal forebrain (BF), hippocampus, and striatum (Bjorness & Greene, 2009; Svenningsson et al., 1997). In addition to the brain, A1Rs are also widely distributed throughout the periphery. A1Rs have been detected in the heart, aorta, liver, kidney, eye, and bladder (Dixon et al., 1996). In the periphery, A1R stimulation primarily decreases heart rate and blood pressure.

Previous research has shown that exogenously administered adenosine provides neuroprotection from various trauma including epilepsy, hypoxia, and ischemia (Basheer et al., 2004; Cunha, 2005; Lynge & Hellsten, 2000; Schubert et al., 1997; Svenningsson et al., 1997; van Helden et al., 1998; Wardas, 2002). These earlier data suggest that adenosine's protective mechanism involves the partial neutralization of neuronal Ca\(^{++}\) overload that leads to cell death (Schubert et al., 1997). Adenosine's inhibitory effect on neuronal excitability has also been exploited for the treatment of drug-resistant epilepsy (Goudet et al., 2003; Huber et al., 2002; Young & Dragunow, 1994). Unfortunately, adenosine therapeutics have not been widely implemented because of the profound reductions in the heart rate and blood pressure that peripheral AR stimulation triggers (Biagioni, 1992; Dunwiddie & Masino, 2001; Schindler et al., 2005). Despite such cardiovascular effects, van Helden et al. (1998) recognized adenosine's potential as a CWNA countermeasure. In their early study, the A1 adenosine agonist (6)-cyclopentyladenosine (CPA) was shown to reduce nerve agent lethality; intramuscular (IM) injections of CPA decreased extracellular ACh levels, diminished seizure activity, and improved survivability in a soman-induced seizure rat model. Other researchers, many of whom are affiliated with van Helden, pursued adenosine in nerve agent models, and identified its neuroprotective properties (Bueters et al., 2002, 2003; Compton, 2004; Joosen et al., 2004; Tuovinen, 2004). However, the mechanism of protection has yet to be agreed upon. Much of the contention can be attributed to the systemic administration method. Since adenosine agonists were injected intramuscularly or subcutaneously, both central and peripheral receptors were stimulated. Consequently, marked decreases in heart rate and blood pressure accompanied the suppression of CNS hyperactivity. Some have concluded that this concomitant decrease in cardiac output protected the brain because very few nerve agents likely circulated to the brain and preserved central AChE activity (Joosen et al., 2004). The results from Bueters et al. (2003) study supported that hypothesis as AChE activity was greater in CPA-treated animals than controls (Bueters et al., 2003). If a reduction in cardiac output was in fact the mechanism of CPA's protection, then similar effects would be expected in VX-exposed animals. However, Bueters et al. (2002) found that CPA at similar doses did not prevent pathologic ACh accumulation after VX exposure as it did against G agents; CPA only delayed the onset of symptoms. That delay could have been a result of AR-induced inhibition of neurotransmitter release and not from concomitant cardiovascular effects. While it is true that a peripherally AR-induced decline in circulation may delay the arrival of nerve agent to the brain, it does not fully explain CPA's observed protective benefits. The mechanism of nerve agent protection may be multi-factorial with the suppression of synaptic transmission and inhibition of neuronal activity playing a significant role (Cunha, 2005; Harrison et al., 2003; Joosen & van Helden, 2007; Wardas, 2002). To better understand adenosine's neuroprotective mechanism and to assess its true efficacy, it is essential that the effects of central and peripheral AR stimulations are separated. Therefore, the main goal for this project was to measure the neuroprotection offered by stimulating central ARs by microinjecting adenosine agonists directly into the brain's ventricular system.

In addition to assessing the neuroprotection that diffuse central AR stimulation offers, this project investigated for the first time if adenosinergic manipulation of the BF could minimize nerve agent-induced excitotoxic activity. In vivo models using electrical and chemical stimuli confirm that the BF is a critical center that promotes wakefulness, and its inhibition decreases brain activity (Lin et al., 2011). Furthermore, the BF excites numerous brain regions; its cholinergic neurons synapse on vital structures such as the cerebral cortex, hippocampus, thalamus, amygdala, and olfactory bulb (Semb, 2000). Hyperactive ACh release from BF terminals may, therefore, be a major promoter of seizure activity. Since approximately 90% of the neurons in the basalis of Meynert are cholinergic and provide the principal source of ACh to the entire cortical surface (Mesulam et al., 1983), and adenosine has been shown to suppress neuronal discharge in the cholinergic BF (Strecker et al., 2000), we hypothesize that BF A1R stimulation may attenuate seizure activity after nerve agent exposure.

### Abbreviations

- ACh, acetylcholine;
- AChE, acetylcholinesterase;
- AR, adenosine receptor;
- AMN, atropine methylnitrate;
- BF, basal forebrain;
- BBB, blood–brain barrier;
- CWN, chemical warfare nerve agent;
- CNS, central nervous system;
- GABA, \( \gamma \)-aminobutyric acid;
- CPA, (6)-cyclopentyladenosine;
- ICV, intracerebroventricular;
- IM, intramuscular;
- IP, intraperitoneal;
- LV, lateral ventricle;
- MTD, maximum-tolerated dose;
- NMDA, \( N \)-methyl-\( D \)-aspartate;
- OP, organophosphorus compound;
- SC, subcutaneous.
Methods

Subjects/animals

Male Sprague–Dawley rats weighing 250–350 g were purchased from Charles River Labs (Kingston, NY) and were individually housed at 21 ± 2 °C and 50 ± 10% humidity with a 12-h light–dark schedule (with lights on at 06:00 h). Laboratory rodent chow and filtered tap water were freely available whenever the animals were in home cages.

Surgery

Using aseptic surgical techniques, animals were prepared first with the insertion of an electronic temperature ID transponder between the shoulder blades subcutaneously (Bio Medic Data Systems Inc., Seaford, DE) and then had wire-electrodes implanted into the skull for recording brain electroencephalographic (EEG) activity. A stereotaxic frame with computer-assisted guidance (Leica Microsystems Inc., Buffalo Grove, IL) was then used to drill two holes into skull and insert 26 gauge cannulae: (1) bilaterally toward the lateral ventricles (LVs) [Atlas Co-ordinates mm (AP, DV, L) (0.0, −4.5, ±1.5)] or (2) bilaterally toward the BF [(−0.35, −8.5, ±2.0)] (Paxinos & Watson, 2009) for drug administration. The rats were allowed to recover for 7 days before experimentation.

Soman seizure rat model

The soman-induced seizure rat model developed at the US Army Medical Research Institute of Chemical Defense (USAMRICD) for nerve-related neuropathology studies was used for this study (Shih, 1990; Shih et al., 1991). This model began with pre-treating animals with 125 mg/kg HI-6 (1,2-hydroxyiminomethyl-1-pyriddino-3-(4-carbamoyl-1-pyriddin-2-oxapranne dichloride) intraperitoneally (IP). Thirty minutes after HI-6 pretreatment, animals were challenged with a subcutaneous (SC) injection of 1.6 × LD50 (180 μg/kg) soman, a dose that produces 100% seizure and convulsion. One minute later, animals were injected IM with 2 mg/kg atropine methyl nitrate (AMN) and treated with microinjections of the adenosine A1 agonist CPA into the LVs or BF. The HI-6 and AMN injections were incorporated into this model to mitigate soman’s peripheral effects and promote 24-h survivability; seizure activity and neuropathology are not affected. CPA was purchased from Tocris Bioscience (Bristol, England). Soman was obtained from the US Army Edgewood Chemical Biological Center (Aberdeen Proving Ground, Aberdeen, MD). HI-6 was purchased from Phoenix Chemical Inc. (Bromborough, England), and AMN was purchased from Wedgewood Pharmacy (Swedesboro, NJ).

The rat’s brain activity was recorded from EEG and used to detect seizure onset. The electrodes implanted into the rat’s skull were connected to recording leads via a connecting plug that attached to the rat’s head with dental cement. At the time of experiment, the rats were placed in individual recording chambers (43 × 30 × 25 cm) where they were able to move freely. Twenty-four hours after exposure, the animals were placed again in these chambers and recorded for an additional 30 min. The EEG data were collected from the CDE 1902 amplifiers and analyzed using Spike2 software (Cambridge Electronic Design, Ltd., Cambridge, England) and custom written MATLAB code. EEG data were continuously assessed by a trained technician who rated the seizure activity as absent or present.

Assessment of neuropathology

Once the in vivo segment of the experiment was completed, the rats were anesthetized with sodium pentobarbital-based euthanasia solution and perfused transcardially with saline followed by 4% paraformaldehyde in PBS. The brain was then extracted and stored in paraformaldehyde. This study implemented two different protocols for histology. The first protocol was used for the maximum tolerated dose (MTD) experiments. These brains were sectioned coronally at 50 μm through the cannulae implantation site, Nissl stained, and then analyzed by a trained pathologist to verify the accuracy of cannulae placement and evaluate toxicity. The second protocol was used for assessing neuropathology in the subsequent soman seizure experiments. Those brains were serial sectioned at 5 μm, stained with hematoxylin and eosin (H&E), and evaluated for neuropathology using established methodology (McDonough et al., 1995). A trained pathologist, who was unaware of treatment paradigm, analyzed and scored four brain regions: the piriform cortex, the thalamus, the dorsal and ventral hippocampus, using the standard rubric: 0 = no lesion; 1 = minimal (1–10%); 2 = mild (11–25%); 3 = moderate (26–45%); 4 = severe (>45%). To further stratify the data and obtain a more comprehensive measure of brain damage, a total score was calculated by summing the four regional scores. A total score of 16 indicates widespread severe damage.

Determination of MTD

Since it was believed that optimal neuroprotection would be achieved at the peak of AR stimulation, the first objective was to determine the MTD of CPA that produced no toxic side-effects when delivered ICV and to the BF. The primary adverse side-effect was expected to be peripheral AR stimulation-induced cardiovascular depression. To detect such a reaction, a pulse oximeter was initially implemented for non-invasively detecting changes in heart rate and oxygenation. However, limitations intrinsic to such a device prevented the acquisition of reliable data. Therefore, alternative methods for detecting toxicity were developed. A dose level was deemed intolerable if any of the following occurred: (1) the mucus membranes, ears, eyes, nose, feet, lips, and tails became cyanotic; (2) respiration was severely depressed; (3) animal did not recover within 24 h; or (4) death occurred.

The MTDs were determined in two parallel dose–response experiments, one for each injection site (the LV and BF), as shown in Table 1. Initial doses were chosen based on the data from previously published experiments that elicited neural inhibition and anticonvulsant effects with adenosine agonists (Anderson et al., 1994; Benington et al., 1995; Methippara et al., 2005; Thakkar et al., 2003; Yildirim & Marangoz, 2007). Four sets of rats were tested in sequential order at each injection site with three rats in each set. Every rat experienced two testing sessions separated by 24 h. CPA was bilaterally injected at a specified dose on day 1 at lower dose. On day 2, the animal received the same drug at an elevated dose.
For group 1 testing LV’s MTD, the total dose of CPA was buffered in 10 μl of multisol (48.5% H2O, 40% propylene glycol, 10% ethanol, and 1.5% benzyl alcohol) and administered bilaterally at a rate of 5 μl/min. For group 2 testing the BF’s MTD, CPA was buffered in 2 μl of multisol and administered bilaterally at a rate of 1 μl/min. Multisol’s safety and non-toxicity at the prescribed volumes and injection methods were verified in a separate experiment, in which two groups of six rats were injected with 10 μl of multisol to the LV and 2 μl of multisol to the BF. Physiologic and histologic analysis determined these vehicle parameters to be safe and non-toxic.

After CPA injection, brain EEG activity was recorded for 5 h, and the behavioral response to adenosine was assessed using a modified functional observation battery (FOB) (Appendix) and a toxic sign test (Table 2). The FOB is a widely used method for assessing pharmacologic reactions; it measures mobility and the overall level of arousal/awareness (Bowen & Balster, 1997; Shih et al., 2006; Youssef & Santi, 1997). The toxic sign test detects more pathophysiologic signs such as tremors, convulsion, salivation, and uncoordinated movement. Twenty-four hours after the second injection, the rat was euthanized. The optimal MTD was determined to be the minimum dose of CPA that consistently produced maximal neural inhibition for each injection site.

The identified MTDs were then each tested in 12 additional rats to verify that a single injection per animal produced central effects without toxicity. Two groups of six animals had the MTDs microinjected as follows: (1) CPA into the LV and (2) CPA into the BF. The physiologic and behavioral responses were recorded for 5 h after injection, the animals were then returned to standard husbandry. Twenty-four hours after microinjection, animals were deeply sedated, perfused, and histologically prepared for pathological assessment. The MTD was verified to be non-toxic, i.e., no neuronal damage beyond what is to be expected from cannulae implantation.

### General stimulation of A1Rs via CPA microinjection into the lateral ventricles

The neuroprotection offered by widespread central AR stimulation was investigated in the soman seizure rat model after MTD determination. The treatment target sites with atlas coordinates and administration regimens are summarized in Table 3. For LVs (Table 3, row 1), 24 animals were tested in two groups of 12. One minute after soman exposure, group 1 received an IM injection of AMN (2 mg/kg) and an intracerebroventricular (ICV) injection of CPA (700 μg; diluted in 10 μl of multisol) at a rate of 5 μl/min. Group 2 also received AMN (2 mg/kg, IM) 1 min after soman exposure, but was injected with multisol instead of CPA to serve as a control. At 0, 4, 8, 15, 30, 45, and 60 min, and thereafter at 30-min increments, behavioral responses were assessed using the FOB (Appendix), and toxic sign scores (Table 2) were recorded for a total of 5 h after soman exposure. EEG was continuously recorded during the 5-h observation period. Twenty-four hours later, an additional 30 min of EEG data were recorded for measuring final brain activity. Rats were then deeply anesthetized, euthanized by exsanguination, and histologically prepared for analysis of neuroprotection efficacy.

### Focal stimulation of BF via A1Rs

The aim for this experiment was to determine if A1R-mediated inhibition of the cholinergic BF would attenuate nerve agent-induced excitotoxicity. Testing was performed on two groups of 12 animals that had canulceae implanted bilaterally in the BF (Table 3, row 2). One minute after soman exposure, both groups were injected with AMN (2 mg/kg, IM). Group 1 then received a microinjection of CPA (350 μg; diluted in 2 μl of multisol) into the BF at a rate of 1.0 μl/min. Group 2 received multisol instead of CPA to serve as a control. EEG was continuously recorded. At 0, 4, 8, 15, 30, 45, and 60 min, and thereafter at 30-min increments, behavioral FOB and toxic sign scores were recorded for a total of 5 h after soman exposure. Twenty-four hours later, following a final 30 min of EEG recording, animals were deeply anesthetized, euthanized, perfused, and histologically prepared for analysis of neuroprotection efficacy.

### Data analysis

The Anderson–Darling normality test was used to determine whether the dataset would be analyzed with a parametric or non-parametric test. Regional differences in pathology severity (i.e., normal, minimal, mild, moderate, or severe) between treatment and control groups were compared using the

#### Table 2. Toxic sign scoring system.

<table>
<thead>
<tr>
<th>Toxic signs</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>0 = Normal, 1 = fasculcation’s, 2 = tremors, 3 = convulsions</td>
</tr>
<tr>
<td>General</td>
<td>0 = Normal, 1 = mildly uncoordinated, 2 = impaired movement, 3 = prostrated</td>
</tr>
<tr>
<td>Salivation</td>
<td>0 = Normal, 1 = salivation</td>
</tr>
<tr>
<td>Lacermination</td>
<td>0 = Normal, 1 = lacerration</td>
</tr>
<tr>
<td>Eye</td>
<td>0 = Normal, 1 = nystagmus</td>
</tr>
</tbody>
</table>

Toxic signs were continuously scored following drug administration during the 5-h observation period on the day of the experiment and also scored again at the 24-h time point.
Toxicology Mechanisms and Methods Downloaded from informahealthcare.com by Wood Technical on 09/22/14

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This occurred at 700 mCPA for the basal forebrain (BF) were microinjected into groups of 12 rats as a treatment to prevent seizure and neuropathology 1 min after a 1.6 × LD50 dose (180 µg/kg) of soman. Results for the treatment groups were compared with control groups that received multisolv instead of an adenosine agonist.

Chi-square test. The total neuropathology scores (0 = normal, 16 = severe) for each treatment group were compared to their controls using the Mann–Whitney test, and compared between treatment groups using the Kruskal–Wallis test. Rates of seizure prevention and survival were compared using Fisher’s exact test. Comparison of the time to seizure and death were done using the Kaplan–Meier survival analysis and log rank test. Differences between treatment and their controls for body temperature were analyzed using the unpaired two-tailed t test. Statistical differences in the severity of toxic motor signs (fasciculation, tremor, and convulsion) between treatment and control groups were detected using a generalized linear model. The level of significance was set at \( p < 0.05 \).

Results

Determination of central MTD

The animals responded to the injections of CPA with a significant reduction in the central activity in a dose-dependent manner. When CPA was administered to the LVs and BF at the lower doses (150 µg for LVs and BF), the animals became lethargic and did not move spontaneously soon after injection. Doses below those values did not elicit notable reactions. As the doses increased, the animals entered a deeper state of sedation to the point where they could not be aroused for the duration of the 5-h observation period (>430 µg for LVs and >150 µg for the BF). Inspection of the EEG data demonstrated that their desynchronous baseline brain activity became more synchronized with lower frequencies and higher amplitudes (shown in Figure 1), similar to that of a deep sleep.

The minimum dose that produced the maximum response was determined to be the MTD for each administration level. This occurred at 700 µg CPA for the LVs group and 350 µg CPA for the BF group. At these doses, the LVs and BF groups experienced a statistically significant decrease in body temperatures during the 5-h observation period \( (p < 0.05) \). Whereas the animals that received only multisolv decreased 1.4 ± 1.1 °C on an average, a likely product of normal circadian variations in temperature, the LVs group decreased 4.7 ± 2.2 °C, and the BF group decreased 3.3 ± 0.6 °C.

The latency between microinjection and behavioral effects shortened as doses escalated to MTD levels. Doses at MTD into the LVs produced maximum inhibition of behavioral and neural activity within 4–8 min and between 8 and 15 min for the BF MTDs. Recovery of central and motor functions varied between treatment regimens. The injection of CPA to the LVs resulted in the long-lasting suppression of neural activity; the animals could not be aroused at the final 5-h assessment time point, but were able to recover by the next morning (>24 h).

The effects of CPA at MTD to the BF began to diminish by the end of the 5-h period.

While the adenosine agonists were administered centrally, there appeared to be some peripheral side-effects such as a reduction in cardiovascular output and development of pallor, particularly in the LVs group. Since only peripheral and not central AR1 stimulation had been shown to have cardiovascular effects (Schindler et al., 2005), a fraction of the CPA likely escaped the CNS and entered peripheral circulation. In contrast to the LVs group, the BF group maintained their pink skin and mucous membrane coloration.

After transcardial perfusion and fixation, the brains were sectioned and stained with Nissl. A trained pathologist then analyzed the sections and verified that CPA treatment was non-toxic and that cannula placement was grossly accurate. For most animals, cannulae were implanted accurately, and there were no signs of infection beyond what was to be expected after an aseptic surgical procedure. However, three LVs rats and two BF rats developed moderate to severe infections from the surgery or had inaccurate cannulae placements. They were removed from the study.
Adenosine agonist to LVs after soman challenge

CPA protected the animals from soman-induced seizure and convulsions. Figure 2 shows EEG tracings from an animal that received CPA treatment and another animal that received multisol after exposure to soman. It illustrates CPA's suppression of soman-induced spike activity. As shown in Table 4(A), the 12 control animals that did not receive CPA but multisol exhibited seizure onset times of 7.2 ± 3.1 min on an average after exposure to a 1.6 × LD50 soman challenge. All 12 control animals also developed convulsions (motor toxic sign = 3) as well as a prostrated posture (general toxic sign = 3). None of the animals that received 700 µg CPA via ICV developed seizure. They were deeply sedated and were not responsive to any external stimuli, similar to the animals that received CPA during the MTD tests. There were no convulsions or behavioral signs of a cholinergic crisis throughout the 5-h monitoring period. Furthermore, there were no indications of a central excitotoxicity; the EEG data resembled that of deep non-random eye movement sleep. In addition to silent neuronal activity, those treated with CPA experienced mild hypothermia. Their temperatures decreased over the 5-h period from a baseline of 37°C to 32.8 ± 1.3°C. That decrease in temperature after treatment was significantly different from the results in the control group, which had an average temperature of 37.2 ± 0.8°C after 5 h (p < 0.01).

CPA’s protection from soman-induced seizure and convulsion continued overnight. Table 5(A) displays survival and neuropathology data for the LVs group. Out of 12 animals, 10 animals that received CPA survived to the 24-h time point and did not show signs of toxicity. Eight of the 10 treated animals were awake and aware of their surroundings; the other two were still in a sleep-like state at the 24-h time point.

Table 4. The effects of adenosine agonists on soman-induced seizure onset time and toxic motor signs.

<table>
<thead>
<tr>
<th></th>
<th>Number seized</th>
<th>Minutes to seizure onset, mean ± standard deviation</th>
<th>Toxic motor sign, mean ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) CPA or multisol vehicle injected into the lateral ventricles (LVs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>12/12</td>
<td>7.2 ± 3.1</td>
<td>3 ± 0 (p &lt; 0.01)</td>
</tr>
<tr>
<td>CPA: LVs</td>
<td>0/12* (p &lt; 0.01)</td>
<td>No seizure activity* (p &lt; 0.01)</td>
<td>0 ± 0* (p &lt; 0.01)</td>
</tr>
<tr>
<td>(B) CPA or multisol vehicle injected into the basal forebrain (BF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>11/12</td>
<td>9.1 ± 2.0</td>
<td>2.9 ± 0.3</td>
</tr>
<tr>
<td>CPA: BF</td>
<td>6/12 (p = 0.07)</td>
<td>20.2 ± 14.7* (p &lt; 0.01)</td>
<td>1.9 ± 1.2* (p &lt; 0.01)</td>
</tr>
</tbody>
</table>

Rats received CPA into the LVs (4A) and the BF (4B) 1 min after exposure to a 1.6 × LD50 dose (180 µg/kg) of soman. Latency to seizure was recorded and toxic motor signs scored. A toxic motor sign of 0 indicates normal behavior, whereas a score of 3 designates convulsions (see Table 2). Statistical differences between treatment and control groups’ seizure rates were calculated using the Chi-square test, seizure onset using the Kaplan–Meier survival analysis and log rank test, and toxic motor signs using a generalized linear model. Statistically significant differences are indicated by *p < 0.05.

Table 5. The effects of adenosine agonists on soman-induced lethality and neuropathology scores at 24 h.

<table>
<thead>
<tr>
<th></th>
<th>Neuropathology – group mean ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h survival</td>
<td>Piriform</td>
</tr>
<tr>
<td>(A) CPA injected into the lateral ventricles (LVs)</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>1/12</td>
</tr>
<tr>
<td>CPA: LVs</td>
<td>10/12* (p &lt; 0.01)</td>
</tr>
<tr>
<td>(B) CPA injected into the basal forebrain (BF)</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>9/12</td>
</tr>
<tr>
<td>CPA: BF</td>
<td>6/12 (p = 0.55)</td>
</tr>
</tbody>
</table>

Twenty-four hours after soman exposure and adenosine treatment, animals that survived were perfused and prepared for histology. A trained neuropathologist graded 4 of the brain regions for damage: the piriform cortex, thalamus, dorsal, and ventral hippocampus. A score of 0 indicates no damage, 1 denotes severe damage in each brain area. Pathology scores for the treatment group were not significantly different from the control according to the Mann–Whitney test (p > 0.05). The Kaplan–Meier survival analysis and log rank test were used to analyze differences in survival 24 h after exposure. ICV treatment produced a significant improvement compared with the control whereas the difference between BF treatment and controls was not significantly different.

*Statistically different responses between treatment and control groups.
†LV histological statistical significance could not be determined with N = 1 for control.
Only one of the 12 control animals survived 24 h and was mildly uncoordinated (general toxic sign = 1) at that time. Applying Fisher’s exact test, the number of surviving animals in the treated group was significantly higher than in the control group ($p < 0.01$). The neuropathology for that control animal indicated moderate to severe damage in the four assessed areas for a total score of 13 (0 = normal, 16 = most severe damage). The CPA-treated animals on an average had a pathology score of $4.9 \pm 1.5$ ($N = 10$). Although the substantial reduction in brain pathology was not significantly different from the control group (due to control, $N = 1$), the LVs treatment pathology scores were significantly ($p < 0.01$) better than the BF controls (Table 5B).

### Adenosine agonist CPA to the BF after soman challenge

The animals that received CPA to the BF as treatment for soman exposure experienced variable protection; seizure and motor response results are reported in Table 4(B). Unlike the LV group that had 100% seizure prevention, six of the 12 animals (50%) in the BF treatment group were protected from seizure. According to Fisher’s exact test, that the rate of seizure prevention is not statistically significant ($p = 0.07$). Those protected animals displayed sleep-like behavior similar to the LV group. Although six treated animals did go into seizure, their latency to seizure onset ($20.2 \pm 14.7$ min) was delayed compared with the control group ($9.1 \pm 2.0$ min). When all animals from the treated and control groups are compared, the difference in seizure latency is statistically significant ($p < 0.01$). One of the 12 control animals did not develop EEG seizure activity but did display signs of soman poisoning: impaired movement, tremors, and convulsions. Three of the six CPA-treated animals that did not seize produced no peripheral signs of toxicity. The other three treatment animals did eventually develop mild tremors approximately 30–45 min after soman exposure. The difference between seizure onset and time of death were statistically different between the BF and LV treatment groups according to the Kaplan–Meier survival analysis and log rank test ($p < 0.05$). The difference in minimum body temperatures between the CPA-treated ($34.3 \pm 2.3$ °C [$N = 12$]) and control BF ($36.4 \pm 1.0$ °C [$N = 12$]) groups was statistically significant according to the $t$ test ($p < 0.05$).

The 24-h survival and neuropathology results for the BF group are described in Table 5(B). Six of the 12 animals treated with CPA survived to the 24-h time point, four of which did not seize the day before. The BF multisol control group experienced better survivability than the LVs; nine of the BF control animals survived to the next day. While the BF-treated group experienced greater lethality than the LV-treated group ($6/12$ versus $2/12$), the localized stimulation of BF ARs provided neuroprotection in addition to preventing seizure. Treated animals that did not seize had zero to minimal neuropathology; their total pathology scores were 0, 0, 4, and 4. Figure 3 illustrates how CPA treatment can protect the brain from neuronal loss if seizures are prevented with either LV (Figure 3, middle) or BF (Figure 3, right) treatments. Similar to what was observed in the control animals that seized, those treated with CPA and seized also developed severe brain damage; their total pathology scores were 14 and 16. Overall, the pathology scores between the BF control and BF treatment groups were not statistically significant ($p = 0.11$). The difference between LV treatment and BF treatment groups also was not statistically different according to the Mann–Whitney test ($p = 0.66$).

### Discussion

This project investigated new neural pathways for protecting the brain from seizure and neuropathology after nerve agent poisoning. We hypothesized that excitotoxic brain activity could be suppressed by (1) widespread stimulation of A1Rs with CPA delivered ICV, or (2) focal stimulation of BF A1Rs with direct CPA microinjections. We believed that the greatest potential for neuroprotection would be achieved when the maximum numbers of ARs were stimulated. Therefore, the first objective was to determine the MTDs for each treatment regimen. After determining the MTDs, both general and focal AR stimulations were tested in a soman seizure rat model with success; seizures and neuropathology were reduced with adenosine agonist treatment. Although direct brain injections of a treatment are not feasible outside the laboratory, this work demonstrated that central AR stimulation is a promising therapeutic mechanism for countering nerve agent neuropathology.

General stimulation of central ARs with CPA microinjected ICV provided the most consistent protection against a soman challenge. The prevention of a central cholinergic crisis can largely be attributed to adenosine’s pre- and post-synaptic actions. A1R pre-synaptic stimulation inhibits the release of ACh and glutamate, thereby limiting the accumulation of excitatory neurotransmitters in the synaptic cleft. A1R post-synaptic stimulation further suppresses neuronal activity and decreases Ca$^{2+}$ influx. Both these actions may block nerve agent-induced hyper-excitatory activity that typically leads to neuropathology. This link between seizure prevention and neuroprotection is supported by the significant reduction in total neuropathology scores from the severe to minimal.

Focal adenosine agonist treatment to the BF displayed mixed results. While some treated animals were completely protected from seizure or convulsion, others had the same...
reaction to soman that the control animals did. These variable
results are consistent with the data collected from the dose
escalation procedure for determining the MTD. While some
animals were profoundly affected by CPA microinjected into
the BF, others in that same group may have had very little
reaction. The most probable explanation for this variation is
inconsistent sites of microinjection. The basal forebrain is a
very small target to hit accurately, even with a computer-
assisted stereotaxic procedure. Differences between animal
shape, size and skull features exacerbate the likelihood for the
placement of the cannulae outside the effective region.
Deviation in expected responses during the MTD tests may
also be due to the desensitization of AR stimulation after the
first day of testing. Because of this effect, future dose-
determination studies should extend recovery times or only
inject once per animal.

Focal BF AR stimulation was not expected to mitigate
soman’s lethal peripheral effects. Since the current therapeu-
tic strategies are able to manage the peripheral but not the
cholinergic crisis, the objective for this intervention was to
prevent seizure and suppress neuropathology. The treat-
ment group was, therefore, as susceptible to soman’s lethal
peripheral effects (e.g. hyper-secretion) as the control group.
Consequently, survival rates were not expected to be signifi-
cantly different. To improve survival rates in addition to
providing neuroprotection, BF AR stimulation should be
combined with therapeutic doses of atropine and/or an AChE
reactivator.

Since ICV-delivered CPA demonstrates more consistent
anti-seizure and neuroprotective effects, general stimulation
of central ARs is a more promising therapeutic approach than
targeting local BF ARs. The differences in survival time and
seizure onset between LV and BF treatment groups were
statistically different but the neuropathology scores were not.
Although focal BF AR stimulation was less effective, the BF
should remain a candidate therapeutic target. It is a known
source of significant cholinergic activity (Semba, 2000), and
in this study, its inhibition protected some animals from
neuropathology. Perhaps pharmacologics with BF selectivity
or alternative techniques such as optogenetics could be
implemented to better evaluate the protective efficacy of BF
inhibition by itself or in conjunction with other therapeutic
mechanisms.

Previous research investigating the therapeutic benefits of
adenosine agonists was confounded by the peripheral side-
effects such as bradycardia and hypotension (Bueters et al.,
2003; Joosen et al., 2004; van Helden et al., 1998). Those
authors concluded that adenosine’s neuroprotective benefit
was likely caused by the concomitant decline in cardiac
output which decreased the amount of nerve agent that
circulated to the brain. To establish that neuroprotection can
be achieved by the stimulation of central A1Rs, we directly
injected adenosine agonists into the brain. While we cannot
make any conclusive statements regarding centrally adminis-
tered adenosine agonists’ effect on cardiac output, it is certain
that the nerve agent circulated to the brain; histology did not
indicate ischemia, and the mucus membranes and tissue were
perfused with blood. Furthermore, the EEG data collected
from soman exposed and non-exposed animals showed a
significant decrease in cortical neuronal activity within 1–
2 min after CPA administration. While it is possible that
cardiac depression may have played a role in delaying the
cholinergic crisis, the results from this study suggest that
CPA’s fast acting suppression of neurotransmitter release and
neuronal inhibition was the primary neuroprotective mechan-
ism. Further studies that measure cardiac output, determine
central AChE activity, and record cortical EEG are needed to
better understand the effects of cardiac depression in this
neuroprotective mechanism.

One observable side-effect of CPA treatment is the steady
decrease in body temperature from 37°C to approximately 28–
30°C over a period of 5 h. Published data suggest this to be a
centrally mediated response, driven in a large part by the
nucleus of the solitary tract (Tupone et al., 2013). The effect
that this decrease in body temperature has on seizure and
pathology prevention is unknown. However, hypothermic
conditions are known to affect cellular activity (Geeraerts &
Vigue, 2009). In some instances, the change in cellular activity
can be beneficial, particularly for cardiac trauma and
brain injury (McIntyre et al., 2003; Peterson et al., 2008;
Schwartz et al., 2012). Furthermore, decreasing body tem-
perature has been shown to suppress seizure activity
(D’Ambrosio et al., 2013; Liu et al., 1993). Consequently,
adenosine’s seizure prevention capacity may not be fully
attributable to a decrease in neurotransmitter release or post-
synaptic inhibition. It is, therefore, necessary to conduct
additional studies where the body temperature is a controlled
variable so that the neuroprotective mechanism can be better
understood.

Although central AR stimulation is a promising medical
countermeasure to nerve agent exposure, direct brain injec-
tions of adenosine agonists are not clinically feasible; drugs
need to be administered intramuscularly in the field. To begin
translating this therapy, future research needs to investigate
alternative administration and dosing protocols. Experiments
should test if the same neuroprotective benefits can be elicited
when CPA is injected systemically. To prevent negative
peripheral side effects while maintaining the positive central
effects, an adenosine antagonist that is impermeable to the
blood–brain barrier could be co-administered. Joosen et al.
(2004) investigated that approach and concluded that the
peripherally acting antagonist reversed the therapeutic benefit
of CPA (Joosen et al., 2004). However, brain EEG data were
not collected in that study. It is possible that the antagonist
only aggrivated peripheral cholinergic symptoms yet central
excitotoxic activity continued to be inhibited and the brain
was protected (Joosen et al., 2004). Further research into
administration methods and side-effect mitigation with EEG
monitoring is needed to elucidate this phenomenon. To
enhance survivability in addition to providing neuroprotec-
tion, greater doses of atropine and AChE reactivators are
recommended for suppressing the nerve agent’s lethal
peripheral effects.

Conclusions

The results from this study support the hypothesis that central
AR stimulation helps to suppresses hyper-excitatory and toxic
neuronal activity in a soman-induced seizure rat model. While the pre- and post-synaptic effects are believed to be the primary mechanism of neuroprotection, AR-induced cardiac depression may have contributed to the neuroprotective effect by delaying the circulation of nerve agent to the brain. Additional studies disentangling these two factors are necessary before the mechanism of protection can be truly identified. Although the specific mechanism remains to be established, central AR stimulation via ICV microinjection of CPA provided consistent neuroprotection; seizures were prevented in all exposed animals. In addition to widespread central AR stimulation, this study investigated basal forebrain AR stimulation as a new mechanism for seizure prevention. Focal microinjection of CPA into the basal forebrain either delayed or prevented seizure onset in the soman model. Although 100% seizure prevention is the objective, the finding that seizure was completely prevented in six of the 12 animals suggests the cholinergic BF is a promising therapeutic target. Improved outcomes from BF stimulation may be achieved with more precise BF delivery, refined dosing regimens, and alternative pharmacological formulations. The positive results from this study motivate further research into this therapeutic approach. Future work aims to elucidate the neuroprotective mechanism and to address delivery and efficacy limitations.

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Declaration of interest

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Appendix

Functional observational battery score sheet

Paw/ear color:
0 Pink, normal
1 Pale
2 Blue

Startle reflex:
Stimulus: Snap your fingers close to and above the rodent’s head
0 jumps, seems startled
1 more energetic response than two – may include vocalization
2 slight reaction, ear flick, or some evidence that a sound was heard
3 no reaction

Righting reflex:
0 normal (immediately rights itself)
1 slightly impaired (>1 s)
2 impaired (>2 s)
3 totally impaired (remains on back)

Animal handling (ease of handling rodent in hand):
0 Difficult, squirming, twisting, attempting to bite, with, or without vocalizations
1 Moderately easy; vocalizations, little, or no squirming
2 Easy, but alert, limbs may be pulled against body
3 Easy, but lethargic
Arousal:
0 Normal (alert, exploratory movements)
1 Somewhat low (some exploratory movements with periods of immobility)
2 Low (some head or body movement)
3 Very low (little or absent)

Gait description:
0 Normal
1 Impairment uncoordinated movement (ataxia), walking on toes, splayed hind limbs, exaggerated hind limb flexion, staggered gait, dragging hind limbs, unable to walk
2 No movement

Approach response:
Stimulus: slowly use pen to approach the rodent from the front and make sure they are aware of the approach.
0 energetic response, possible vocalizations
1 slow approach, sniffing or turning away
2 no reaction