8-(3-Chlorostyryl)caffeine May Attenuate MPTP Neurotoxicity through Dual Actions of Monoamine Oxidase Inhibition and A2A Receptor Antagonism*

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Caffeine and more specific antagonists of the adenosine A2A receptor recently have been found to be neuroprotective in the MPTP (1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine) model of Parkinson’s disease. Here we show that 8-(3-chlorostyryl)caffeine (CSC), a specific A2A antagonist closely related to caffeine, also attenuates MPTP-induced neurotoxicity. Because the neurotoxicity of MPTP relies on its oxidative metabolism to the mitochondrial toxin MPP⁺, we investigated the actions of CSC on striatal MPTP metabolism in vivo. CSC elevated striatal levels of MPTP but lowered levels of the oxidative intermediate MPDP⁺ and of MPP⁺, suggesting that CSC blocks the conversion of MPTP to MPDP⁺ in vivo. In assessing the direct effects of CSC and A2A receptors on monoamine oxidase (MAO) activity, we found that CSC potently and specifically inhibited mouse brain mitochondrial MAO-B activity in vitro with a Ki value of 100 nM, whereas caffeine and another relatively specific A2A antagonist produced little or no inhibition. The A2A receptor independence of MAO-B inhibition by CSC was further supported by the similarity of brain MAO activities derived from A2A receptor knockout and wild-type mice and was confirmed by demonstrating potent inhibition of A2A receptor knockout-derived MAO-B by CSC. Together, these data indicate that CSC possesses dual actions of MAO-B inhibition and A2A receptor antagonism, a unique combination suggesting a new class of compounds with the potential for enhanced neuroprotective properties.

The neurodegeneration of Parkinson’s disease (PD) targets dopaminergic neurons that project to the striatum (1). In PD the progressive loss of striatal dopamine leads to a progressive deterioration in motor function. Despite the availability of dopamine-replacement strategies that generally offer considerable symptomatic relief early in the disease, as yet no therapy has been shown to slow the underlying neurodegenerative process.

Adenosine A2A receptor antagonists recently have attracted attention as potential neuroprotective agents because of a remarkable convergence of epidemiological and laboratory data that link the A2A receptor to the development of PD (2). Prospective studies of several large populations have shown that caffeine consumption is associated with a reduced risk of developing PD (3, 4). The risk of PD decreased with increasing prior intake of coffee or of caffeine from other sources and was independent of smoking status or other potential confounding factors. Notably, consumption of decaffeinated coffee was not related to PD risk (4).

The possibility that the reduced risk of PD among caffeine consumers is due to a neuroprotective effect of caffeine has been supported by our finding that caffeine can reduce dopaminergic neuron toxicity in a mouse model of PD (5). Low doses of caffeine can attenuate the loss of striatal dopamine and of dopamine transporter (DAT) binding sites induced by 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP). The neuroprotection by caffeine, a nonspecific adenosine receptor antagonist (6), could be mimicked by relatively specific adenosine A2A receptor antagonists but not an A1 antagonist (5, 7). A2A receptor knockout mice also were resistant to MPTP-induced depletion of striatal dopamine. Together these laboratory data have suggested a potential neurobiological basis for the inverse association between caffeine use and PD.

Here we examine the neuroprotective properties of 8-(3-chlorostyryl)caffeine (CSC), a selective and potent A2A antagonist closely related to caffeine (8) in the MPTP model of PD (9). Because the neurotoxicity of MPTP requires its oxidation to the active toxin, the 1-methyl-4-phenylpyridinium (MPP⁺) species, by monoamine oxidase B (MAO-B), we investigated the effects of CSC on MPTP metabolism in vivo and on MAO activity in vitro. The results of these studies offer new insight into structure-activity relationships for MAO-B inhibitors and suggest a

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1 The abbreviations used are: PD, Parkinson’s disease; MPTP, 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine; CSC, 8-(3-chlorostyryl)-caffeine; MPP⁺, 1-methyl-4-phenylpyridinium; MAO, monoamine oxidase; A2A KO, adenosine A2A receptor knockout; WT, wild-type; CFX, 1,3-dipropyl-8-cylopropylxanthine; DMPX, 3,7-dimethyl-1-propargylxanthine; MPDP⁺, 1-methyl-4-phenyl-2,3-dihydropyridinium; MMPT, 1-methyl-4-(1-methylpyrrrol-2-yl)-1,2,3,6-tetrahydropyridine; DAT, dopamine transporter.
novel class of dual-function compounds with enhanced potential for the treatment of PD.

**EXPERIMENTAL PROCEDURES**

**MPTP and CSc Treatment Paradigms**—Male C57Bl/6 mice (25–28 g; 2–3 months old) received a single intraperitoneal injection of 20–40 mg/kg MPTP-HCl (or saline) or four intraperitoneal injections of 20 mg/kg MPTP-HCl (or saline) two hours apart. Ten minutes prior to each MPTP dose mice were pretreated with CSc or vehicle (a fresh mixture of dimethyl sulfoxide (15%), ethoxylated castor oil (15%); Alkamuls EL-620, Rhodia, Cranberry, NJ, and water).

**Derivation and Breeding of A2AR Knockout (A2AR KO) Mice**—A2AR KO mice were generated using a standard displacement target vector as described previously (10). Briefly, chimeric A2AR KO mice (P0) derived from 129-Steel embryonic stem cells were bred to C57Bl/6 mice, resulting in mice of mixed C57Bl/6 × 129-Steel backgrounds. To effectively eliminate the potentially confounding influence of the 129-Steel background, the mixed line was then repeatedly back-crossed to pure C57Bl/6 mice over six generations yielding a near congenic (N6) C57Bl/6 line. A2AR KO (−/−) and wild-type (WT, +/+ ) littersmates (both male and female) from N6 heterozygote (+/−) intercrosses were used in this study.

**Dopamine and Serotonin Measurements and DAT Autoradiography**—Seven days after treatment, mice were sacrificed by rapid cervical dislocation and assayed for striatal dopamine or serotonin content and [3H]mazindol (DAT) binding as described previously (5).

**Brain MPTP, MPDP**<sub>3</sub>, and MPP**<sub>3</sub>** Determinations—Striatal concentrations of MPTP, MPDP<sub>3</sub>, and MPP<sub>3</sub> were measured as described previously (5, 11).

**Monoamine Oxidase Activity**—Intact mitochondria prepared from C57Bl/6 mouse brain and human placenta served as sources of MAO. The mitochondrial fractions were prepared as described by Salach and Weyer (12) with minor modifications and were stored at −70 °C. Before use, the mitochondrial homogenate was suspended in sodium phosphate buffer (0.1 M, pH 7.4) containing 50% (w/v) glycerol. The protein concentrations (25–60 mg/ml) were determined by the method of Bradford (13).

**K**<sub>a</sub> and V<sub>max</sub> determinations of the MAO-B-catalyzed oxidation of the MAO-B-selective substrate MPTP (25–400 μM) were carried out in brain mitochondrial preparations (final protein concentration of 0.3 mg protein/ml) in 0.1 mM sodium phosphate buffer pH 7.4, 500 μl final volume; 30 min at 37 °C) obtained from WT and A2AR KO mice (pooled tissues of three mice in each case; determinations in duplicate). The reactions were terminated by the addition of 20 μl of perchloric acid (70% v/v), and the samples were centrifuged at 16,000 × g for 5 min. The supernatant fractions were removed and assayed for the MAO-B-generated dihydroxydipyrindinium metabolite (MPDP<sub>3</sub>) by measuring the absorbance at 345 nm spectrophotometrically (ε = 16,000 M<sup>−1</sup> cm<sup>−1</sup>) (14, 15).

The activity ratios of MAO-A to MAO-B were determined in mouse brain mitochondrial preparations from A2AR KO and WT (each ratio represents averaged duplicate values from three separate animals). To measure MAO-B activity, the MAO-A present in the mouse brain mitochondria was inactivated by preincubating the preparation (1.2 mg of protein/ml) with 3.3 × 10<sup>4</sup> M dorgloryl hydrochloride, an MAO-A-selective inhibitor, for 15 min at 37 °C in 0.1 M, pH 7.4 sodium phosphate buffer (15). This solution was added to an equal volume of solution of the non-selective MAO-A/B substrate 1-methyl-4-(1-methylpyrrol-2-yl)-1,2,3,6-tetrahydroyridine (MMTP; final concentration of 2 mM) also in sodium phosphate buffer (500 μl final volume). Following a 30-min incubation period at 37 °C, the reactions were terminated by the addition of 20 μl of 70% perchloric acid. The resulting mixtures were centrifuged, and the concentrations of the enzyme-generated dihydroxydipyrindinium metabolite (MMPD<sub>3</sub>) were measured spectrophotometrically at 420 nm (ε = 25,000 M<sup>−1</sup> cm<sup>−1</sup>) (15, 16). The MAO-A activity was estimated in the same way, using mouse brain mitochondria pretreated with the MAO-B-selective inhibitor (R)-deprenyl (3.3 × 10<sup>−7</sup> M) (15). The total MAO activity was determined by carrying out this assay in the absence of inactivator.

**RESULTS AND DISCUSSION**

**The Effect of CSc on MPTP Neurotoxicity**—The loss of striatal dopamine induced by MPTP (administered in four 20 mg/kg intraperitoneal doses two hours apart) in C57Bl/6 mice was significantly attenuated by CSc (5 mg/kg intraperitoneal 10 min prior to each MPTP dose; Fig. 1A, left panel). CSc also attenuated dopamine loss induced by a single high dose of MPTP-HCl (40 mg/kg), and it did so in a dose-dependent manner with complete protection observed at and above 20 mg/kg CSc (Fig. 1B). In contrast to dopamine, serotonin levels in the striatum were not altered by MPTP (Fig. 1A, right panel), highlighting the selectivity of the toxin for dopaminergic neurons. CSc had no effect on baseline levels of dopamine or serotonin in the striatum.

In addition to a biochemical marker of nigrostriatal integrity (dopamine) DAT density in the striatum, an anatomical marker of nigrostriatal innervation, was also assessed. MPTP induced a loss of striatal DAT ([<sup>3</sup>H]mazindol) binding sites commensurate with that of striatal dopamine content. This loss was significantly attenuated by pretreatment with CSc (Fig. 1C). Taken together with prior findings that mice pretreated with other specific A2AR antagonists and those lacking functional A2AR receptors showed reduced MPTP toxicity (5, 7), these data seem to suggest that CSc protects dopaminergic neurons by blocking A2AR receptors. Moreover, the locomotor stimulating effect of 5 mg/kg CSc was completely blocked in A2AR receptor knockout mice, lending further support to the possibility that the neuroprotective effect of CSc at this dose depends on its A2AR antagonist properties.

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*J.-F. Chen and M. A. Schwarzschild, unpublished observations.*
The Effect of CSC on MPTP Metabolism in Vivo—Because the neurotoxicity of MPTP requires its oxidation to the active toxin MPP⁺, we examined the effects of CSC pretreatment on MPP⁺ levels in the striatum (Fig. 2A). Mice were treated with vehicle or CSC 5 min prior to the first of four MPTP injections. 90 min after the last MPTP injection, striatal MPP⁺ levels were significantly lower in CSC-treated mice compared with those treated with vehicle. Thus CSC leads to decreased MPP⁺ levels in the striatum, which may contribute to its attenuation of MPTP toxicity.

To investigate further the potential mechanism underlying attenuated MPP⁺ levels in the striatum, we also determined the effects of CSC on striatal levels of MPTP and MPDP⁺ following intraperitoneal MPTP treatment. After crossing the blood-brain barrier, MPTP is oxidized in a reaction catalyzed by MAO-B to yield the relatively unstable 1-methyl-4-phenyl-2,3-dihydropyridinium intermediate MPDP⁺, which in turn oxidizes further to the stable active toxin MPP⁺ (9). 15 min after a single MPTP injection, striatal levels of MPTP and MPDP⁺ peak while striatal MPP⁺ levels are starting to rise (11). Pretreatment with CSC (5 mg/kg) significantly increased MPTP levels and decreased both MPDP⁺ and MPP⁺ in striatum. Striatal levels of MPTP, MPDP⁺, and MPP⁺ were determined 90 min after the last of four MPTP doses (20 mg/kg intraperitoneal, two hours apart) with CSC (5 mg/kg) or vehicle administered 10 min prior to each MPTP dose (n = 7–8; panel A), 15 min after a single MPTP dose (20 mg/kg intraperitoneal) with CSC (5 mg/kg) or vehicle administered 10 min prior (n = 9–10; panel B), or 15 min after the last of four MPTP doses (20 mg/kg, intraperitoneal each, two hours apart) with CSC (5 mg/kg) or vehicle administered 10 min prior to each MPTP dose (i.e. 75 min before the determination made in panel A; n = 11; panel C). * indicates p < 0.05 when comparing to the vehicle plus MPTP group.
MPP⁺ levels in striatum at 15 min post-MPTP administration (Fig. 2B), an effect also seen with the MAO-B inhibitor, 7-nitroindazole (27).

To explore the in vivo metabolism of MPTP in the more complex (but pathophysiologically more relevant) multiple-dose toxin paradigm, we quantified striatal metabolites 15 min after the four injections of MPTP dose toxin paradigm, we quantified striatal metabolites 15 min after the fourth MPTP injection increased levels of MPTP (Fig. 2C). This result was consistent with previous reports (17, 18) that single MPTP administration increased levels of MPTP and MPDP⁺. To investigate the effect of CSC on MAO-B activity, we determined MAO-B activity in brain preparations derived from A2A receptor KO mice and their WT littermates. Haines plots of the effects of CSC on both activities indicate a Kᵩ of ~100 nM for the inhibitory action of CSC on MAO-B activity in extracts devoid of A2A receptors (i.e. in those of KO mice) as well as in standard (WT) preparations.

**The Effect of CSC on MAO Activity in Vitro**—To investigate the possibility of a direct effect of CSC on MAO activity, we assayed mitochondrial MAO-A and MAO-B activities in the presence of CSC across a range of concentrations. Fig. 3 shows that CSC potently inhibits MAO-B activity in a mitochondrial preparation from mouse brain with a Kᵩ value of ~100 nM, a value comparable with that of the most potent known competitive MAO-B inhibitors (20). In contrast to MAO-B, MAO-A (from human placenta) was not significantly inhibited by CSC.

To determine whether other adenosine receptor antagonists also share this unexpected property of MAO-B inhibition we compared the effect of CSC with those of caffeine (a nonspecific adenosine receptor antagonist), DMPX (another relatively specific adenosine A₂A receptor antagonist), and CPX (a relatively specific adenosine A₁ receptor antagonist) on MAO-B activity. In studies using a mitochondrial preparation from mouse brain with MPTP as substrate, CSC potently inhibited MAO-B activity in vivo with a Kᵩ of ~100 nM, whereas caffeine, DMPX, and CPX produced little if any inhibition with estimated Kᵩ values of 0.7, 1, and >4 mM, respectively. These findings demonstrate that, in addition to its A₂A antagonist properties, CSC also is a
potent and selective inhibitor of MAO-B. Our observation that 1 μM CSC completely blocks MAO-B activity in primary cultures of brain glia, which express few if any A2A receptors, further suggests the possibility that CSC inhibits MAO-B directly.

CSC Inhibits MAO-B Independently of A2A Receptors—Although the MAOs are not known to couple to receptors, the standard mitochondrial preparations used to identify the MAO inhibitory properties of CSC are likely to contain A2A receptors through which CSC could indirectly inhibit MAO-B. The recent demonstration of an ultrastructural localization of A2A receptors to intracellular organelle membranes within striatal neurons (21) underscores the need to address this possibility. To assess A2A receptor involvement in the effect of CSC on MAO-B, we took advantage of an A2A KO model of A2A receptor function (10). We first compared the MAO activities in the brains of A2A KO and WT mice using MMTP as substrate (Table I). Under V_{max} conditions in the presence of appropriate inhibitors, no significant difference was observed in the total MAO activity or the activities of MAO-A and MAO-B. In a separate experiment the K_{m} and V_{max} values of MAO-B-catalyzed oxidation of MPTP also were found to be indistinguishable in brain mitochondrial preparation from the A2A KO mice and WT littermates (Table I). The normal kinetics of MAO activity in A2A KO (as well as the absence of MAO inhibitory activity of the A2A antagonist DMPX) argue against a modulatory effect of A2A receptors on MAO-B activity.

We also examined the inhibitory effects of CSC on MAO-B activity of mitochondria prepared from the brains of A2A KO mice and their WT littermates. Fig. 4 shows that CSC is just as potent in its inhibition of A2A KO MAO-B as it is in its inhibition of WT MAO-B (with a K_{i} of ~100 nM for each). These data confirm the hypothesis that the novel MAO-B inhibitory action of CSC is independent of its well-established antagonistic action on A2A receptors. A direct inhibition of MAO-B explains the reduction in the levels of MPDP\(^+\) and the active toxin MPP\(^+\) in vivo when systemic MPTP is administered with CSC (Fig. 2) but not with other A2A antagonists (5, 7). Thus, the neuroprotective effect of CSC in the MPTP model of PD may rely in part on this A2A receptor-independent inhibition of MAO-B.

The unexpected finding of dual MAO-B inhibitory and A2A receptor antagonistic function in a xanthine-derived structure (28) together with further structure-function relationship studies now underway should help to identify possible relationships between the active sites of these two proteins.

The pharmacological significance of a single structure capable of both MAO-B inhibition and A2A antagonist activity is underscored by ongoing clinical trials that are based on these two individual anti-parkinsonian strategies. Moreover, the targeting of either of these proteins may be particularly beneficial in treating PD because both MAO-B inhibitors and A2A antagonists possess neuroprotective as well as symptomatic therapeutic potential (22). The neuroprotective benefits of dual-action agents offering MAO inhibition and A2A antagonist activity may extend beyond PD because preclinical studies have suggested possible therapeutic effects of both MAO inhibitors and A2A antagonists in a range of neuropsychiatric disorders from stroke to depression (10, 23, 24). The recognition that CSC acts as an MAO-B inhibitor as well as an A2A antagonist also may help to explain an unexpected observation on the brain distribution of isotopically labeled CSC (25). This compound, which was designed as a positron emission tomography ligand for measuring A2A receptor density in humans, was found to label most heavily the relatively A2A receptor-poor region of the ventral medulla in addition to the A2A receptor-rich striatum. That the ventral medulla contains a high density of serotonergic neurons known to express high levels of MAO-B (26) fits well with the present finding that CSC acts on MAO-B as well as the A2A receptor.

In conclusion, the present data indicate that CSC possesses dual actions of MAO-B inhibition and A2A receptor antagonism, a unique combination suggesting a new class of compounds with the potential for enhanced therapeutic potential in PD and other neuropsychiatric disorders.

REFERENCES


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3 K. Xu, J.-F. Chen, and M. A. Schwarzschild, unpublished data.