Further Studies on the Role of Metabolites in MDMA-induced Serotonergic Neurotoxicity

Melanie Mueller, Jie Yuan, Anne Felim, Anne Neudörffer, Frank T. Peters, Hans H. Maurer, Una D. McCann, Martine Largeron and George A. Ricaurte

Department of Neurology (MM, JY, GR) and Psychiatry and Behavioral Sciences (UM), Johns Hopkins University School of Medicine, Baltimore, MD 21224; UMR 8638 associée au CNRS (AF, AN, ML), Université Paris Descartes, 75270 Paris cedex 06, France; Department of Experimental and Clinical Toxicology (MM, FP, HM), Institute of Experimental and Clinical Pharmacology and Toxicology, Saarland University, D-66421 Homburg (Saar), Germany
Abstract

The mechanism by which the recreational drug (±) 3, 4-methylenedioxymethamphetamine (MDMA) destroys brain serotonin (5-HT) axon terminals is not understood. Recent studies have implicated MDMA metabolites but their precise role remains unclear. To further evaluate the relative importance of metabolites versus the parent compound in neurotoxicity, the present study explored the relationship between pharmacokinetic parameters of MDMA, 3,4-methylenedioxyamphetamine (MDA), 3,4-dihydroxymethamphetamine (HHMA) and 4-hydroxy-3-methoxymethamphetamine (HMMA) and indexes of serotonergic neurotoxicity in the same animals. The present study also further evaluated the neurotoxic potential of 5-(N-acetylcystein-S-yl)-HHMA (5-NAC-HHMA), an MDMA metabolite recently implicated in 5-HT neurotoxicity. Lasting serotonergic deficits correlated strongly with pharmacokinetic parameters of MDMA (Cmax and AUC), more weakly with those of MDA, and not at all with those of HHMA or HMMA (total amounts of the free analytes obtained after conjugate cleavage). HHMA and HMMA could not be detected in the brains of animals with high brain MDMA concentrations and high plasma HHMA and HMMA concentrations, suggesting that HHMA and HMMA do not readily penetrate the blood brain barrier (either in their free form or as sulfate or glucuronic conjugates) and that little or no MDMA is metabolized to HHMA or HMMA in the brain. Repeated intraparenchymal administration of 5-NAC-HHMA did not produce significant lasting serotonergic deficits in the rat brain. Taken together, these results indicate that MDMA and, possibly, MDA are more important determinants of brain 5-HT neurotoxicity in the rat than HHMA and HMMA, and bring into question the role of metabolites (including 5-NAC-HHMA) in MDMA neurotoxicity.
Introduction

Despite much research, the mechanism by which (±) 3,4-methylenedioxymethylamphetamine (MDMA; “Ecstasy”) destroys brain serotonin (5-HT) axon terminals remains unknown. One hypothesis that has recently drawn considerable attention is that a drug metabolite is involved (Perfetti et al., 2009; Capela et al., 2009). Over the years, various metabolites of MDMA and related drugs have been evaluated for possible 5-HT neurotoxic activity (Figure 1). Steele et al. (1991), for example, assessed the neurotoxic potential of 3,4-dihydroxymethamphetamine (HHMA, which they designated alpha-methylepinine) and concluded that it alone was not responsible for MDMA neurotoxicity. Similarly, McCann and Ricaurte (1991) evaluated the neurotoxic properties of alpha-methyldopamine and 3-O-methyl-alpha-methyldopamine [alternatively designated as 3,4-hydroxyamphetamine (HHA) and 4-hydroxy-3-methoxyamphetamine, respectively] and reached similar conclusions.

Based on theoretical considerations and the identification of MDMA metabolites that are analogs of the well established neurotoxin 6-hydroxydopamine (Lim and Foltz (1991a; 1991b), the neurotoxicological properties of 6-hydroxy-3,4-methylenedioxymethylamphetamine (6-OHMDMA) and 2,4,5-trihydroxymethamphetamine (THMA) were investigated (Zhao et al., 1992; Johnson et al., 1992). 6-OHMDMA, administered intraventricularly and intraparenchymally, was found to be without effect. In contrast, THMA (same routes of administration) produced substantial depletions of 5-HT and DA which lasted for at least 5-7 days beyond drug administration (Zhao et al., 1992; Johnson et al., 1992). Given the known selectivity of MDMA for 5-HT neurons, results with THMA were deemed to be inconclusive but
suggestive of the possibility that THMA might play a role in MDMA neurotoxicity, because the effect on DA might have been related to the route of THMA administration (Zhao et al., 1992).

As mentioned above, there has recently been a resurgence of interest in the possibility that MDMA metabolites might play a role in MDMA neurotoxicity. A role for systemically formed MDMA metabolites is often inferred from the observation that direct injection of MDMA into brain fails to reproduce the 5-HT neurotoxic effects of peripherally administered MDMA (Schmidt and Taylor, 1988; Esteban et al., 2001). A report that cytochrome P450 modulators (SKF-525A and phenobarbital) influence MDMA-induced 5-HT depletions (Gollamudi et al., 1989) is also often cited to support the role of a drug metabolite. However, in that study, SKF-525A and phenobarbital altered acute (3 h) but not lasting effects of MDMA on brain 5-HT neurons.

Hiramatsu and colleagues (1990) were the first to report metabolism of MDMA to a reactive quinone which formed a glutathione adduct that might be responsible for MDMA neurotoxicity. More recently, other glutathione and N-acetylcystein conjugates of catechol metabolites of MDMA and MDA have been identified and implicated in MDMA neurotoxicity (Miller et al., 1997; Bai et al., 1999; Jones et al., 2005; Capela et al., 2007; Pizarro et al., 2008). Of these, 5-(N-acetylcystein-S-yl)-N-methyl-alpha-methylidopamine [here designated as 5-(N-acetylcystein-S-yl)-HHMA (5-NAC-HHMA)] has been the metabolite most strongly implicated (Jones et al., 2005; Erives et al., 2008).
MDMA metabolism proceeds mainly through two pathways, at different rates in different species (see Meyer et al., 2008). The first pathway involves \( O \)-demethylation of MDMA to HHMA, followed by \( O \)-methylation to 4-hydroxy-3-methoxymethamphetamine (HMMA), with subsequent \( O \)-conjugation with sulfate or glucuronic acid. The second pathway involves initial \( N \)-demethylation to MDA, followed by deamination and oxidation to the corresponding benzoic acid derivatives conjugated with glycine. As mentioned above, catechol metabolites of MDMA and MDA (HHMA and HHA) can be further oxidized to their corresponding quinones, which can then form adducts with glutathione and other thiol-containing compounds (Hiramatsu et al., 1990; Monks et al., 2004).

The purpose of the present study was several-fold: 1) To assess the relative importance of the parent compound (MDMA) versus its major metabolites (HHMA, HMMA, MDA) in MDMA neurotoxicity; 2) To determine which pharmacokinetic parameter of MDMA or its metabolites best predicts subsequent 5-HT neurotoxicity; and 3) To further assess the 5-HT neurotoxic potential and selectivity of the catechol thioether, 5-NAC-HHMA.
Methods

Animals: Male Sprague-Dawley rats (Harlan, Indianapolis, IN, USA) that were 49 – 69 days of age and weighed 200 – 299 grams were used for all experiments. Animals were housed three per cage (except during drug treatment and after surgical cannula implantation, when they were housed singly) in standard polypropylene cages (17 inches x 10 inches x 8 inches) at 22 ± 2 °C ambient temperature (except during drug treatment, when the ambient temperature was 25 °C), with free access to food and water. Animals were maintained on a 12:12 h light:dark cycle. The facilities for housing and care of the animals are accredited by the American Association for the Assessment and Accreditation of Laboratory Animal Care. Animal care and experimental manipulations were approved by the Institutional Animal Care and Use Committee at the Johns Hopkins University School of Medicine, and were in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

Study design: To assess the relationship between MDMA and its major metabolites (MDA, HHMA and HMMA) and brain 5-HT neurotoxicity, pharmacokinetic parameters of MDMA, HHMA, HMMA and MDA were measured during the period of drug exposure and related to indexes of brain 5-HT neurotoxicity (depletions of 5-HT and 5-HIAA) measured one week later in the same animals. The reason for the one week delay was that MDMA and metabolites are known to alter 5-HT and 5-HIAA levels acutely [by inducing 5-HT release, blocking its reuptake and, possibly, by blocking metabolism of 5-HT by monoamine oxidase (MAO)]. Thus, “acute” depletions of 5-HT and 5-HIAA may not necessarily reflect neurotoxicity. Indeed, Chu and colleagues (1996) have already shown that there is no relationship between “acute” depletions of 5-HT and brain MDMA and metabolite levels,
probably because at least some of the perturbations seen in 5-HT levels while MDMA is still in the tissue are related to pharmacological (rather than toxic) effects of MDMA on the 5-HT neuron. By contrast, depletions of 5-HT and 5-HIAA documented at least one week after drug exposure (when drug and metabolites are no longer on board) are known to be related to 5-HT axon loss (Molliver et al., 1990). To further assess the 5-HT neurotoxic potential of 5-NAC-HHMA, the compound was administered directly into the striatum, at a dose and frequency previously reported to produce lasting 5-HT deficits. Possible involvement of the 5-HT transporter in the anticipated 5-HT deficits was assessed with fluoxetine, a 5-HT uptake blocker that is known to protect against MDMA neurotoxicity (Schmidt, 1987).

**Drugs and Reagents:** Racemic MDMA hydrochloride was obtained through the National Institute on Drug Abuse (Rockville, MD, USA). Racemic HHMA hydrochloride and methanolic solutions (1000 mg/l) of racemic MDMA hydrochloride and racemic MDA hydrochloride were purchased from Lipomed (Cambridge, MA, USA). Methanolic solutions (1000 mg/l) of racemic HMMA and methanolic solutions (100 mg/l) of racemic MDMA-d5 and MDA-d5 were obtained from Cerilliant (Round Rock, TX, USA). Fluoxetine, 4-hydroxymethamphetamine (pholedrine), 4-methylcatechol, ethylenediaminetetraacetic acid disodium salt dihydrate (EDTA), 5, 7-dihydroxytryptamine (5,7-DHT), and glucuronidase type HP-2 form helix pomatia (glucuronidase activity ≥ 100.000 units/mL and sulfatase activity < 7.500 units/mL) were obtained from Sigma-Aldrich (Saint Louis, MO, USA). Sodium metabisulfite (SMBS) was obtained from E. Merck (Darmstadt, Germany). Perchloric acid (PCA) was obtained from J.T. Baker (Phillipsburg, NJ, USA). Xylazine was obtained from Butler Animal Health Supply (Dublin, OH, USA). Ketamine was supplied by Phoenix Pharmaceuticals (St. Joseph, MO,
USA). 5-NAC-HHMA was synthesized as recently described (Felim et al., 2007). The authenticity of the MDMA, HHMA, HMMA, MDA, and 5-NAC-HHMA samples used in the present studies was confirmed using liquid chromatographic/mass spectrometric (LC/MS) methods to determine the corresponding pseudomolecular ions and at least one fragment ion for each compound. Analysis was performed in full scan (mass range from 100 – 1000) to check for presence of possible impurities.

**Drug treatment:** MDMA was given orally (by gavage) at a dose of 20 mg/kg at an ambient temperature of 25 °C. For studies involving intrastriatal administration of 5-NAC-HHMA, rats received four consecutive doses of either 21 or 42 nMoles of the compound, with a 12 h interval between each dose. This particular dosage regimen was selected because it is the same one as that used by Bai et al. (1999) who first reported on the neurotoxic potential of 5-NAC-HHMA. In an additional experiment involving 5-NAC-HHMA, rats were pretreated with 10 mg/kg fluoxetine (i.p.) 15 min prior to each intrastriatal injection of 21 nMoles of 5-NAC-HHMA. In the latter experiment, the well-established selective 5-HT neurotoxin, 5,7-dihydroxytryptamine (5, 7-DHT) was used as a positive control and was also given intrastriatally, at a dose of 52 nMoles. Doses refer to the base form of all drugs.

**Blood sampling and plasma preparation:** For determination of plasma concentrations of MDMA (and its metabolites) and their pharmacokinetic profiles, blood was sampled at various times after MDMA administration. Blood collection times were selected so as to allow for accurate determinations of drug pharmacokinetic parameters. For logistical reasons, blood was sampled at 0.75, 1.5, 3, 6, and 12 h after MDMA administration in one group of animals (N=15);
in a second group of rats (N= 9), blood was collected at 1, 3, 6, 8, 9, and 24 h after MDMA treatment. At each time point, approximately 0.2 ml of blood was collected by means of retro-orbital bleeding. One week after MDMA treatment, all animals were sacrificed for regional brain 5-HT and 5-HIAA determinations, as detailed below. A third group of animals (N=8 at each time point) was used for determination of plasma and brain concentrations of MDMA (and its metabolites). In this group of animals, the major point of interest was the relationship between plasma and brain MDMA and metabolite concentrations. Blood sampling in this experiment occurred at 1, 3, 6, 8, and 24 h MDMA treatment. Blood samples were dispensed into 2 ml BD Vacutainer hematology tubes, containing 4mg K3 EDTA solution (Becton-Dickinson, Franklin Lakes, NJ, USA), and stored on ice for up to 30 min, until centrifuged. Samples were centrifuged at 1100 g for 10 min. Plasma was withdrawn using a 5 ml 3/4 Pasteur pipette and decanted into a 1.5 ml polypropylene tube and SMBS (250 mM) was added at a volume of 30µl/ml plasma to minimize oxidation of the compounds of interest. Plasma samples were stored at -20 °C until assay.

**Measurement of plasma MDMA and metabolite concentrations:** Plasma MDMA, MDA, HHMA and HMMA concentrations were determined as recently described (Mueller et al., 2007). Briefly, aliquots (100 µl) of rat plasma were preserved with 20 µl of SMBS (250 mM) and 10 µl of EDTA (250 mM). After addition of 100 µl of an aqueous solution of the racemic internal standards (ISs) MDMA-\textsuperscript{d5}, MDA-\textsuperscript{d5}, and pholedrine (1.0 µg/ml, each) and 10 µl of glucuronidase solution, samples were mixed (15 s) on a rotary shaker and left at 50°C for 90 min to perform conjugate cleavage. After cooling to room temperature, 20 µl of 4-methylcatechol (1 mg/ml) was added, and samples were briefly vortexed. Perchloric acid (10 µl) was then added
and the samples were mixed again on a rotary shaker for 15 s to perform protein precipitation. The samples were centrifuged (16 000g for 5 min), and the supernatant was transferred to autosampler vials. Aliquots (5 µl) were injected into an LC-MS system and amounts of MDMA and metabolites were determined. The linear range for each analyte was 20-1000 ng/mL MDMA, HHMA, HMMA and 10-500 ng/mL MDA. Method accuracy was greater than 80%. The lowest point of the calibration curve was the limit of quantification (LOQ) of the method (20 ng/mL for MDMA, HHMA, and HMMA each, and 10 ng/mL for MDA).

**Measurement of brain MDMA and metabolite concentrations:** For determination of brain concentrations of MDMA, HHMA, HMMA and MDA, samples were prepared and analyzed according to a recently published LC-MS method (Mueller et al., 2008). Values for HHMA and HMMA represent total amounts (i.e., amounts measured after cleavage of sulfate and glucuronic acid conjugates). In particular, aliquots of rat cortices (approximately 100 mg) were weighed and for each mg of tissue, 10 µL of ISs solution were added. After homogenizing using a Polytron homogenization unit (model PT 10-35, Kinematica Inc., Bohemia, NY, USA, 15s, setting 6), 10 µL of glucuronidase solution were added, the samples were briefly mixed (15s) on a rotary shaker and left at 50 ºC on a waterbath for 90 min to perform conjugate cleavage. After cooling to room temperature, the samples were centrifuged (16 000g for 10 min), and the supernatant was transferred to autosampler vials. Aliquots (5 µl) were injected into the LC-MS system. The linear range for each analyte was 2-100 µg/g MDMA, 1-50 µg/g MDA, and 0.1-5 µg/g HHMA and HMMA. Method accuracy was greater than 90%. The lowest point of the calibration curve was defined as the LOQ of the method (2 µg/g for MDMA, 1 µg/g for MDA, and 0.1 µg/g for ...
HHMA and HMMA). Values for HHMA and HMMA represent free amounts (i.e., amounts measured after cleavage of sulfate and glucuronic acid conjugates).

**Calculation of pharmacokinetic parameters:** Peak plasma concentrations (C_max), times of peak plasma concentration (T_max), area under the concentration-time curve (AUC), and the elimination half-lives (T_{1/2}) were obtained using the pharmacokinetic functions for Microsoft Excel (developed by Usansky et al., http://www.boomer.org/pkin/xcel/pkf/pkf.doc).

**Surgical cannula implantation:** Animals were anesthetized with xylazine (25 mg/kg, i.p.) and ketamine (35 mg/kg i.p.). Guide cannulae (20 GA, Plastic One, Roanoke, VA, USA) were surgically implanted into the right striatum (anteroposterior, 0.4 mm; mediolateral, -3.0 mm; dorsoventral, 4.0 mm; Paxinos and Watson, 1986). Cannulae were fixed to the skull with dental acrylic (Ortho-Jet, Lang Dental, Wheeling, IL, USA) and two stainless steel screws. Dummy cannulae were placed in the guide cannulae and animals were individually housed and allowed a 7-day recovery period.

**Intrastriatal administration of 5-NAC-HHMA:** The dummy cannulae were replaced with an internal cannulae (24 GA, Plastic One) connected to PE 20 tubing which in turn were connected to 1 µL Hamilton 7000 series glass syringew (Hamilton Company, Reno, NV, USA) containing the various injection solutions. Artificial cerebrospinal fluid (aCSF) served as vehicle served, and was prepared as previously described by Miller et al. (1997). In a first experiment rats received either 1 µL of aCSF (control group, n = 8), 21nMoles of 5-NAC-HHMA (n = 10), 42nMoles of 5-NAC-HHMA (n = 5), or 52nMoles of 5,7-DHT (positive control group, n = 4).
In a second experiment, animals were pretreated with either saline (0.3 mL) or fluoxetine (15 mg/kg i.p.) 15 min prior to intrastriatal injections. Following pretreatment, either 1 µL aCSF or 21 nMoles of 5-NAC-HHMA were injected into the striatum (total four groups, n = 6 in each group). One µL of the drug solution was injected manually into the striatum (anteroposterior, 0.4 mm; mediolateral, - 3.0 mm; dorsoventral, 5.0 mm; Paxinos and Watson, 1986) at a rate of 0.2 µL over 5 min for a total of four consecutive doses, with each dose administered 12 h apart. After the injection was completed, the internal cannulae were left in the striatum for an additional 2 min. Animals were awake but gently restrained during the injections. Following injection, the dummy cannulae were replaced. Animals were sacrificed two weeks later for determination of 5-HT and 5-HIAA levels, as described below.

**Determination of brain 5-HT and 5-HIAA concentrations:** Samples of cortex and striatum were analyzed for their content of 5-HT and 5-HIAA one or two weeks after drug treatment, as previously described (Mechan et al. 2006).

**Statistics:** The significance of differences between means was determined using a two-tailed student’s t-test or ANOVA followed by Tukey’s multiple comparison test. Correlations were explored using Pearson’s product moment correlation. Statistical analyses were performed using Prism, Version 3.02 (GraphPad Software, Inc. San Diego, CA, USA). Differences and correlations were considered significant if p < 0.05.
Results

Plasma profiles of MDMA and its major metabolites following a single neurotoxic dose of MDMA (20 mg/kg; p.o.) are shown in Figure 2, and pharmacokinetic parameters are specified in Table 1. As shown in the figure and table, MDMA had the highest peak plasma concentrations (C_{max}), followed by MDA, then HHMA and HMMA. In particular, the C_{max} of MDMA was about two-fold higher than that of MDA, and approximately four times and three times higher than that of HHMA and HMMA, respectively.

Relative proportions of MDMA and metabolites were somewhat different when AUC, instead of C_{max}, values were considered. Specifically, the AUC of MDMA was only 1.14 higher than that of MDA and only approximately two-fold higher than that of HHMA and HMMA.

The T_{1/2} of MDMA after oral administration was 5.8 ± 3.5 h. If a biphasic decay process is assumed, the estimated decay rate of the first phase was 3.0 hours and the estimated decay rate of the second phase was 10.5 hours. The T_{1/2} of MDA, HHMA and HMMA could not be computed because, within the time window of measurement (0.75 to 24 h), there were insufficient data points in the terminal elimination phase of the plasma profiles of MDA, HHMA and HMMA (Figure 2).

Rats treated with a single 20 mg/kg oral dose of MDMA showed a significant depletion of brain 5-HT one week later (Figure 3). On average, cortical 5-HT was reduced by 38%. There were comparable depletions of 5-HIAA (Figure 3). The 20 mg/kg dose of MDMA produced a 0.5 to 1°C elevation in core temperature.
Figure 4 shows results of analyses exploring the relationship between the C\text{max} of the parent compound and its various metabolites and cortical 5-HT deficits. Of note, these were within-subject analyses, as plasma drug concentrations and subsequent brain 5-HT deficits were measured in the same animal. Significant relationships were observed between the C\text{max} of MDMA and MDA and subsequent 5-HT depletions, such that animals with the highest peak plasma concentrations of MDMA and MDA had the largest depletions of brain 5-HT (Figure 4). In contrast, there were no significant relationships between peak plasma concentrations of HHMA or HMMA and brain 5-HT depletions one week later (Figure 4).

As the relative proportions of MDMA to MDA, HHMA and HMMA varied depending upon whether their respective C\text{max} or AUC values were considered (see above), we also explored the relationship between the AUC of the parent compound (MDMA) and its various metabolites (MDA, HHMA, HMMA) and subsequent 5-HT depletions. Only the AUC of MDMA correlated significantly with subsequent cortical 5-HT deficits (Figure 5).

Given that brain concentrations of MDMA and/or metabolites are, in all likelihood, more proximate causes of brain 5-HT neurotoxicity than plasma concentrations of the various compounds, we next measured brain concentrations of MDMA and its various metabolites (MDA, HHMA and HMMA) in the brains of rats treated with the same dose of MDMA used in the previous experiment (20 mg/kg, p.o.). Brain concentrations of MDMA and metabolites in this study were determined at various times after MDMA administration (1, 3, 6, 8 and 24 h), necessarily in different groups of animals at each time point (n = 8 at each time point). As
shown in Figure 6 (top), only MDMA and MDA were detected in the brain at all time points examined. There was a high correlation between brain and plasma concentrations of MDMA and MDA (R=0.88 and 0.98, respectively). HHMA and HMMA were not detectable in the brains of animals that had high concentrations of HHMA and HMMA in plasma and high concentrations of MDMA in brain. The limit of detection for HHMA and HMMA in brain tissue was 0.1 µg/g.

Because previous research has implicated the catechol thioether metabolite of MDMA, 5-NAC-HHMA, in MDMA neurotoxicity (Jones et al., 2005; Erives et al., 2008), we also performed studies to further assess the 5-HT neurotoxic potential of 5-NAC-HHMA and its selectivity. In these studies, we administered 5-NAC-HHMA directly into the striatum, at two different doses (21 and 42 nMoles). The established 5-HT neurotoxin, 5, 7- DHT (also administered directly into the striatum), served as a positive control. As anticipated, 5,7 DHT produced a sizeable depletion of striatal 5-HT two weeks later. In contrast, 5-NAC-HHMA produced a modest, non-significant decrease in striatal 5-HT content that was neither dose-related (Figure 7) nor influenced by fluoxetine (Figure 8). No significant differences were observed in 5-HIAA levels in controls and rats treated with 5-NAC-HHMA groups, with or without fluoxetine pretreatment (data not shown).
Discussion

The potential role of metabolites in MDMA neurotoxicity has been a topic of recent interest (Perfetti et al., 2009; Capela et al., 2009). This is the first study to assess the relationship between pharmacokinetic parameters (C_{max} and AUC) of MDMA and its major metabolites (HHMA, HMMA and MDA) and 5-HT neurotoxic effects in the same animal. Results indicate that MDMA-induced 5-HT neurotoxicity is most closely related to concentrations of MDMA, with a weaker relationship to concentrations of MDA, and no relationship to concentrations of HHMA or HMMA. Indeed, whereas levels of MDMA and MDA in brain were five- to ten-fold higher than those in plasma, brain HHMA and HMMA could not be detected, despite high plasma HHMA and HMMA concentrations in the same animals. These results, which are consistent with those of Escobedo et al. (2005), suggest that HHMA and HMMA do not readily penetrate the blood brain barrier (either in their free form or as sulfate or glucuronic conjugates) and indicate that there is little or no brain metabolism of MDMA to HHMA or HMMA. Taken together, these observations and those of others (Steele et al., 1991; Escobedo et al., 2005) cast doubt on the view that HHMA and HMMA are directly involved in MDMA neurotoxicity (Goni-Allo et al., 2008) but leave open the possibility that MDA or a catechol-thioether metabolite of MDMA might be involved.

Although pharmacokinetic parameters of both MDMA and MDA were found to be significantly associated with subsequent 5-HT neurotoxicity, the association with MDMA appeared to be more robust. In particular, both the C_{max} and AUC of MDMA were significantly and highly correlated with subsequent 5-HT deficits, whereas only the C_{max} of MDA was correlated with 5-HT loss (at a lower significance level). Potential reasons that only MDA C_{max},
but not AUC, are related to subsequent 5-HT depletion are: 1) PK parameters for MDA AUC may not be sufficiently precise, due to insufficiently long sampling times; 2) $C_{\text{max}}$ may be the relevant pharmacokinetic parameter for predicting neurotoxicity; 3) MDA may not be involved in MDMA neurotoxicity. The current results do not permit definitive conclusions regarding the relative importance of MDMA and MDA in the neurotoxic process as it occurs in rats, as the pharmacokinetic parameter that best predicts 5-HT neurotoxicity is unknown. At least in rats (see below), both MDMA and MDA may contribute in an additive or synergistic fashion to 5-HT neurotoxicity, because they interact with many of the same neuronal systems and elements, and MDA is known to have 5-HT neurotoxic potential (Ricaurte et al., 1985).

Comparisons of the current data, collected in rats, to pharmacokinetic data collected in primates (squirrel monkeys and humans) may also shed light on the relative importance of the parent compound (MDMA) and MDA in 5-HT neurotoxicity. In particular, in squirrel monkeys, MDA is a minor metabolite (3 to 5%), yet this species also develops MDMA-induced 5-HT neural injury. Although within-subject studies involving pharmacokinetic and neurotoxicity measures have not been conducted in humans, the pharmacokinetics of MDMA in humans are similar to those in squirrel monkeys, and demonstrate relatively low levels of MDA production (Kolbrich et al., 2008). A growing body of data indicates that human recreational MDMA users are susceptible to MDMA neurotoxicity (McCann et al., 1998; McCann et al., 2005; Kish et al., 2009) and, taken together with the pharmacokinetic data in humans, argue against a major role for MDA in MDMA-induced neurotoxicity, at least in primates.
As alluded to above, it is not known which pharmacokinetic parameter ($C_{\text{max}}$, AUC, or other) of MDMA (or MDA) most influences 5-HT neurotoxicity. However, there are clues in the literature that certain thresholds must be met for neurotoxicity to develop. In particular, intravenous dosages of MDMA that engender high, but short-lived, peak concentrations of MDMA (Banks et al., 2007; Mueller et al., unpublished observation) do not appear to be associated with neurotoxicity (Fantegrossi et al., 2004), presumably because of insufficiently long duration of drug action. Similarly, repeated low doses of MDMA that fail to achieve a certain threshold concentration would not be expected to produce neurotoxic effects, even though, when considered in aggregate, they would lead to high AUC values. With respect to duration of action, co-administration of a selective 5-HT reuptake inhibitor (fluoxetine) up to 6 hours after MDMA administration can protect from 5-HT neurotoxicity, suggesting that key events for the development of neurotoxicity take place within 6 hours of drug administration (Schmidt et al., 1987). When these previously published data are considered along with the present findings, the most parsimonious explanation is that peak plasma drug concentrations must reach a threshold for a certain period of time (3-6 hours) for 5-HT neurotoxicity to develop. Stated differently, it is likely that both $C_{\text{max}}$ and AUC are important determinants of MDMA-induced 5-HT neurotoxicity.

While precise threshold neurotoxic $C_{\text{max}}$ and AUC MDMA values have yet to be determined, a working model of a potential mechanism underlying MDMA neurotoxicity can be proposed. This model, which emerges from data discussed above, relates the two principal outcome measures of the present study: pharmacokinetic parameters of MDMA and its metabolites during the period of drug (metabolite) exposure and 5-HT axonal markers (5-HT and
5-HIAA) measured one week later. The model assumes that, for neurotoxicity to occur, drug (or metabolite) must interact with the 5-HT transporter for 3-6 hours. Further, it assumes that a certain threshold drug level must be achieved and maintained during the 3-6 hours that critical toxic drug/transporter interactions appear to take place. Importantly, the model makes no assumption about serotonin or other monoamine or metabolite levels during the period of drug exposure. It does, however, allow for a role of core temperature, with high temperatures facilitating and low core temperatures retarding toxic drug/transporter interactions.

It should be emphasized that correlation does not imply causation, that the relationship between MDMA (and MDA) and 5-HT deficits could be coincidental, and that other drug effects may be the most important mediators of neurotoxicity [e.g. transporter based ion dysregulation, as postulated for methamphetamine (Callahan et al., 2001)]. As noted earlier (see Introduction), there are data indicating that when MDMA is injected directly into the brain, neurotoxicity does not develop. While this might be viewed as incontrovertible evidence that MDMA is not the major mediator of MDMA-induced 5-HT injury, it is possible that peripheral pharmacological effects not reproduced by central administration (e.g., increased temperature) are required for neurotoxicity to occur. Also, it is likely that centrally administered MDMA is only toxic when its concentration and duration of action are similar to those after peripheral administration.

The thioether metabolite of HHMA, 5-NAC-HHMA, has been directly implicated in MDMA neurotoxicity (Jones et al., 2005; Erives et al., 2008). In the present study, 5-NAC-HHMA, when administered repeatedly and in large doses into the striatum did not lead to statistically significant 5-HT depletions. Moreover, the modest effect of 5-NAC-HHMA on
striatal 5-HT was neither dose related, nor blocked by the 5-HT uptake inhibitor, fluoxetine, which is known to protect against MDMA neurotoxicity (Schmidt et al., 1987). These observations argue against a pivotal role for 5-NAC-HHMA in MDMA-induced 5-HT neurotoxicity, but leave open the possibility that it may work in conjunction with MDMA or MDA in the neurotoxic process. Alternatively, 5-NAC-HHMA may require the presence of MDMA and/or elevated body temperature to be toxic, although an earlier study (McCann and Ricaurte, 1991) also suggested that thioether adducts of HHA are not likely to be responsible for serotonergic neurotoxicity.

The present findings with 5-NAC-HHMA are at odds with a previous study that found this compound produced dose-related depletions of 5-HT in rats (Jones et al., 2005). The reasons for this discrepancy are not entirely clear. We established the identity of 5-NAC-HHMA has by HPLC and NMR spectra [methods available in the supporting information of Felim et al (2007)]. Further, the stability of 5-NAC-HHMA was confirmed after each injection by using LC/MS to monitor the abundance of its molecular mass ion [MH$^+$] and one fragment ion ($m/z = 343$ and $m/z = 181$ respectively). Another potential reason for discrepant findings might be inadequate drug delivery of an unstable compound to target tissues. However, 5,7 DHT (which is also unstable and has a tendency to oxidize) was injected using identical methods and was found to produce robust 5-HT deficits. Finally, it may be relevant that 5-NAC-HHMA used in the present studies was prepared using a biomimetic electrochemical synthetic method (Felim et al., 2007), whereas 5-NAC-HHMA used by Jones and colleagues (2005) was prepared with mushroom tyrosinase, which yields a different ratio of 5-NAC-HHMA diastereoisomers (Pizarro et al., 2007).
2008). Additional research will be required to determine the basis for discrepant findings between the present study and that of Jones and colleagues (2005).

In conclusion, the present results indicate that MDMA-induced 5-HT neurotoxicity is most closely related to plasma and brain concentrations of MDMA, with a weaker relationship to concentrations of MDA, and no relationship to concentrations of HHMA or HMMA. The present results also indicate that the pharmacokinetic parameter of MDMA that best predicts subsequent 5-HT neurotoxicity is $C_{\text{max}}$, although AUC is also a good predictor and both peak levels and duration of action are likely to be important. Notably, neither HHMA nor HMMA could be detected in brain, despite high concentrations of these MDMA metabolites in plasma, indicating that HHMA and HMMA do not readily penetrate the blood brain barrier. As brain concentrations of MDMA in the same animals were 5-10-fold higher than those in plasma, the absence of measurable amounts of HHMA and HMMA in their brain also suggests that biotransformation of MDMA to HHMA and HMMA does not occur to any appreciable degree in the brain. Finally, repeated intrastriatal administration of 5-NAC-HHMA produced a modest, non-significant decrease in striatal 5-HT content that was neither dose-related nor influenced by fluoxetine. Taken together, these results favor the view that MDMA and, possibly, MDA are the compounds that trigger brain 5-HT neurotoxicity in rats, and suggest that HHMA, HMMA and the catechol thioether metabolite, 5-NAC-HHMA do not play a crucial role in MDMA-induced 5-HT neurotoxicity \textit{in vivo}.
Acknowledgments

We thank George Hadtzidimitriou and Gianluigi Tanda for their help with these experiments.
References


Esteban B, O'Shea E, Camarero J, Sanchez V, Green AR, Colado MI (2001) 3,4-Methylenedioxymethamphetamine induces monoamine release, but not toxicity, when administered centrally at a concentration occurring following a peripherally injected neurotoxic dose. *Psychopharmacology (Berl)* **154**:251-60.


Lim HK, Foltz RL (1991b) Ion trap tandem mass spectrometric evidence for the metabolism of


Footnotes

This work was supported by NIH grants DA 05707 and DA01796401 (GR) and joint financial support of the Mission Interministérielle de Lutte contre la Drogue et la Toxicomanie (MILDT) and the Institut National de la Santé et de la Recherche Médicale (INSERM). (Appel à projets commun 2007 MILDT-INSERM « Recherche sur les drogues et la toxicomanie ») (ML).

A.F. thanks MILDT together with INSERM for a PhD grant.
Legends for Figures

Figure 1: Metabolites of MDMA and related drugs that have been evaluated for 5-HT neurotoxic potential. 1Ricaurte et al. (1985), 2Zhao et al. (1992), 3Johnson et al. (1992), 4 Elayan et al. (1992), 5Steele et al. (1991), 6Escobedo et al. (2005), and 7McCann and Ricaurte (1991). With the exception of MDA, the only other MDMA metabolite of the various metabolites shown known to have 5-HT neurotoxic potential is THMA. However, recent efforts in our laboratory to identify THMA in the brain of rats given neurotoxic doses of MDMA (20-60 mg/kg, PO) have been unsuccessful, even though THMA given intracerebroventricularly can be readily measured in the rat brain for up to 3 hours after administration using LC/MS methods (unpublished observation).

Figure 2: Plasma profile of MDMA and its metabolites (MDA, HHMA, and HMMA) in rats (N=24) given a single oral dose of MDMA (20 mg/kg). Concentrations of HHMA and HMMA represent total amounts of free HHMA and HMMA obtained after conjugate cleavage, as detailed in Methods.

Figure 3: 5-HT (left panel) and 5-HIAA (right panel) concentrations in rats treated with saline (n = 17) or a single oral dose of MDMA (20 mg/kg) (N=24) one week previously. *Designates P < 0.05 (two-tailed Student’s t-test).

Figure 4: Relationship between C_{max} of MDMA, MDA, HHMA or HMMA and cortical 5-HT depletion. Rats received a single oral dose of MDMA (20 mg/kg). One week later, cortical 5-
HT levels were determined. The figures reflect within-subject analyses, as drug plasma levels and cortical 5-HT levels were measured in the same animal (N=24). $R =$ Pearson correlation coefficient. P values are shown.

*Figure 5:* Relationship between AUC of MDMA and its various metabolites and cortical 5-HT depletion in rats given a single oral dose of MDMA (20 mg/kg) and sacrificed one week later. The results reflect within-subject analyses, as drug plasma levels and cortical 5-HT levels were measured in the same animal (N=24). $R =$ Pearson correlation coefficient. P values are shown.

*Figure 6:* Plasma and brain profiles of MDMA, MDA, HHMA and HMMA in rats given a single oral dose of MDMA (20 mg/kg) and sacrificed after 1, 3, 6, 8, and 24 h, respectively (N=8 at each time point). Determinations were made after conjugate cleavage, as detailed in *Methods.* HHMA and HMMA could not be detected in brain tissue. Limit of detection for HHMA and HMMA was 0.1µg/g.

*Figure 7:* Concentrations of 5-HT in the ipsilateral and contralateral striatum of rats that received direct unilateral intrastriatal injections of 5-NAC-HHMA at two different concentrations (21 or 42 nMoles) two weeks previously. Each dose of 5-NAC-HHMA was injected four times, with a 12 hr interval between each injection. 5-NAC-HHMA was dissolved in aCSF, at concentrations shown, shortly before each injection. Control animals received unilateral intrastriatal injections of an equivalent volume aCSF. The n for each treatment group was: aCSF (N=8), 21 nMoles 5-NAC-HHMA (n = 10), 42 nMoles 5-NAC-HMMA (N=5). A positive control group consisted of animals that received a single intrastriatal injection of 52
nMols 5, 7-DHT (N=4). Only the effect of 5,7-DHT was significant. * Designates significant relationship.

**Figure 8:** Concentrations of 5-HT in the ipsilateral striatum of rats that received direct unilateral intrastriatal injections of 5-NAC-HHMA (21 nMoles) alone or in combination with fluoxetine (10 mg/kg; i.p.; 15 min prior to 5-NAC-HHMA) two weeks previously. 5-NAC-HHMA was injected four times, with a 12 hr interval between each injection. 5-NAC-HHMA was dissolved in aCSF shortly before each injection. Control animals received unilateral intrastriatal injections of an equivalent volume aCSF. N=6 for each treatment group.
Table 1: Pharmacokinetic parameters of MDMA and its metabolites in plasma of rats given a single oral dose of 20 mg/kg MDMA. Values represent the mean ± SD (N=24).

<table>
<thead>
<tr>
<th>Analyte</th>
<th>C_{max} (ng/mL)</th>
<th>AUC (ng/mL · h)</th>
<th>T_{max} (h)</th>
<th>T_{1/2} (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDMA</td>
<td>652 ± 368.7</td>
<td>4469 ± 1694.2</td>
<td>2.5 ± 1.7</td>
<td>5.8 ± 3.5</td>
</tr>
<tr>
<td>MDA</td>
<td>361 ± 174.1</td>
<td>3926 ± 1348.1</td>
<td>5.7 ± 2.0</td>
<td>ND</td>
</tr>
<tr>
<td>HHMA</td>
<td>170 ± 46.9</td>
<td>2383 ± 897.8</td>
<td>7.2 ± 2.4</td>
<td>ND</td>
</tr>
<tr>
<td>HMMA</td>
<td>201 ± 67.6</td>
<td>2409 ± 846.2</td>
<td>7.7 ± 2.1</td>
<td>ND</td>
</tr>
</tbody>
</table>
Table 2: Pharmacokinetic parameters of MDMA and MDA in brain of rats given a single oral dose of 20 mg/kg MDMA (N=8 at each time point).

<table>
<thead>
<tr>
<th>Analyte</th>
<th>$C_{\text{max}}$ (ng/mg)</th>
<th>AUC (ng/mg · h)</th>
<th>$T_{\text{max}}$ (h)</th>
<th>$T_{1/2}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDMA</td>
<td>3315</td>
<td>386839</td>
<td>1.0</td>
<td>14.3</td>
</tr>
<tr>
<td>MDA</td>
<td>1761</td>
<td>297299</td>
<td>6.0</td>
<td>14.3</td>
</tr>
</tbody>
</table>
**Figure 1**

<table>
<thead>
<tr>
<th></th>
<th>MDA $^1$</th>
<th>6-OHMDMA $^{2,4}$</th>
<th>THMA $^{2,3,4}$</th>
<th>HHMA $^{3,5,6}$</th>
<th>HMMA</th>
<th>HHA $^7$</th>
<th>HMA $^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R$_1$</td>
<td>H</td>
<td>CH$_3$</td>
<td>CH$_3$</td>
<td>CH$_3$</td>
<td>CH$_3$</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>R$_2$</td>
<td></td>
<td></td>
<td>OH</td>
<td>OH</td>
<td>CH$_3$</td>
<td>OH</td>
<td>CH$_3$</td>
</tr>
<tr>
<td>R$_3$</td>
<td></td>
<td></td>
<td>OH</td>
<td>OH</td>
<td>OH</td>
<td>OH</td>
<td>OH</td>
</tr>
<tr>
<td>R$_4$</td>
<td></td>
<td></td>
<td>OH</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>
Figure 3

5-HT

Saline | MDMA
---|---
0.3 | 0.2

5-HIAA

Saline | MDMA
---|---
0.2 | 0.1

* indicates statistically significant difference from Saline group.
**Figure 4**

**MDMA**

- $R = -0.68; p = 0.0003$

**MDA**

- $R = -0.50; p = 0.014$

**HHMA**

- $R = 0.22; p = 0.298$

**HMMA**

- $R = -0.087; p = 0.687$
Figure 5

**MDMA**

- $R = -0.55; p = 0.005$

**MDA**

- $R = -0.31; p = 0.146$

**HHMA**

- $R = 0.31; p = 0.137$

**HMMA**

- $R = 0.30; p = 0.155$

**Graphs**

- 5-HT [Percent Control] vs. AUC [hr·ng/mL]
Figure 7

Ipsilateral

Contralateral

Serotonin [ng/mg]

<table>
<thead>
<tr>
<th></th>
<th>aCSF</th>
<th>5-NAC-HHMA 21nmol x 4</th>
<th>5-NAC-HHMA 42nmol x 4</th>
<th>5,7-DHT 52nmol x 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates a significant difference.
Figure 8